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AIR FORCE MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND

CONTRACT AF 33(615)-2460
PROJECT 7381; TASK 738103

THE BISMUTH TELLURIDE-BISMUTH SELENIDE SYSTEM

M. NEUBERGER

DATA SHEET DS-147
JAN 1966

EPIC

ELECTRONIC
PROPERTIES
INFORMATION
CENTER

HUGHES

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CULVER CITY, CALIFORNIA

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FOREWORD

The Electronic Properties Information Center (EPIC) was established in June 1961 at Hughes Aircraft Company, Culver City, California. It is operated under contract with the Air Force Materials Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Ohio. The Contract was initiated under Project No. 7381, Task No. 738103, with Mr. R. F. Klinger acting as Project Engineer.

The EPIC Information Analysis Center is a center for the collection, review and analysis of the scientific and technical literature on the electrical and electronic properties of materials. Its major function is to evaluate, compile and publish the experimental data from that literature. Through the medium of a series of publications such as Data Sheets, Special Reports, State-of-the-Art Reports, Computer Bibliographies, and services including special studies, answers to technical inquiries, research support is provided to the DoD community. EPIC input is primarily from the open literature. A large number of abstract journals, in addition to about 40 other journals, and the unclassified report literature are completely searched.

This report consists of the compiled data sheets on the Bismuth Telluride-Bismuth Selenide System. A full list of EPIC publications to date appears at the end of the report.

The author wishes to acknowledge the assistance afforded by Dr. J. J. Grossman in reviewing the experimental data, and the contribution of Mr. E. Schafer in the thorough pre-publication review of the compilation. The supporting assistance of other members of the EPIC staff, in particular, Mrs. D. Gough, Mr. Thomas Lyndon, and Mr. W.S. Hodge, is gratefully acknowledged.

ABSTRACT

These data sheets present a compilation of a wide range of electronic properties for the bismuth telluride-bismuth selenide system. Electrical properties include conductivity, dielectric constant, Hall coefficient, and mobility. Emission data have been broken down into the varied electron and photon emissions which result from application of electromagnetic energy over a wide spectrum. Energy data include energy bands, energy gap, and energy levels, as well as effective mass tables, and work function. The optical properties include absorption, reflection, and the refractive index. Other magnetic data and irradiation effects are presented, as well as several related physical phenomena, such as piezoelectric properties, Debye temperature and electronic specific heat. Thermoelectric properties, thermal conductivity and figure of merit tables and graphs are especially presented. Each property is compiled over the widest possible range of parameters including bulk and film form, from references obtained in a thorough literature search.

A summary of crystal structure and phase transitions has been included.

This report has been reviewed and is approved for publication.

Emil Schafer
Emil Schafer, Assistant Head
Electronic Properties Information Center

for J. F. Atwood
John W. Atwood
Project Manager

TABLE OF CONTENTS

INTRODUCTION

The initial step in the preparation of this data sheet was the retrieval, by means of modified coordinate index, of all bismuth telluride-bismuth selenide system literature in the EPIC file. Bibliographies were also reviewed to ensure the inclusion of all relevant literature. Those papers containing primary source data were selected unless only secondary references were available. If equally valid data were available from several sources, all were given. Data were rejected when considered questionable because of faulty or dubious measurements, unknown sample composition, or if more reliable and inclusive data were available from another source. Selection of data was based upon evaluation of that which was most representative, precise, reliable and inclusive over a wide range of parameters. The addition of new data to a material compilation requires a reappraisal of the reported values. Older data may be deleted in light of the new data.

Within every property section we have tried to include every available parameter and range of experimental condition in the literature. Information on test conditions and sample specification are extracted from the article. Some slight alterations in units and presentation may be made to facilitate comparison with other experimental data.

In the thermoelectric properties section, electric conductivity and thermal conductivity graphs, (where available for the same samples) are presented with thermal emf data in order to facilitate calculation of figure of merit values. Cross-referencing of germane information is also provided.

Within the individual properties, arrangement has generally been to show the pure sample data followed by the effects of dopants (in alphabetical

order). Doping, per se, however, is often not a qualifying factor, and graphs may be arranged or grouped according to experimental parameters.

In presenting tabular data, values are variously arranged. In some cases it is by dopant, in others by magnitude of numerical value. On occasion, however, the values from one reference may be grouped for comparison.

The references, from which the data are drawn, are shown by accession number below each graph, with the full bibliographic citation tabulated at the end of the data sheets. The bibliography is listed by accession number.

An introductory section on the crystallographic structure and phase diagrams of this system includes lattice arrangements and correlation with thermoelectric properties.

CRYSTALLOGRAPHY

Bismuth telluride occurs naturally as tellurobismuthite in irregular plates or foliated masses. It is soft, with a metallic lustre; the (0001) cleavage is perfect, so that all measurements are made either normal or parallel to that plane. The hexagonal symmetry indicates that the electronic properties are anisotropic. This anisotropy is very marked in optical measurements [Ref. 3124]; dielectric constant [Ref. 10299]; electrical conductivity [Ref. 631], [electrical conductivity normal to the (0001) cleavage plane is .1 of that parallel to the (0001)]; magnetoelectric measurements [Ref. 19045]; reflectivity [Ref. 18221]; and thermoelectric emf [Ref. 19827].

Bismuth selenide occurs naturally as orthorhombic guanajuatite in acicular crystals or granular foliated or fibrous masses. The cleavage is distinct on (010) or (001). The mineral is soft with metallic lustre. The synthetic material is rhombohedral and apparently isostructural with the telluride.

Wyckoff states that both the bismuth telluride and the bismuth selenide are rhombohedral crystals with a one molecule unit. The corresponding hexagonal cell contains three molecules and the molecule is considered to have atom layers along the c-axis.

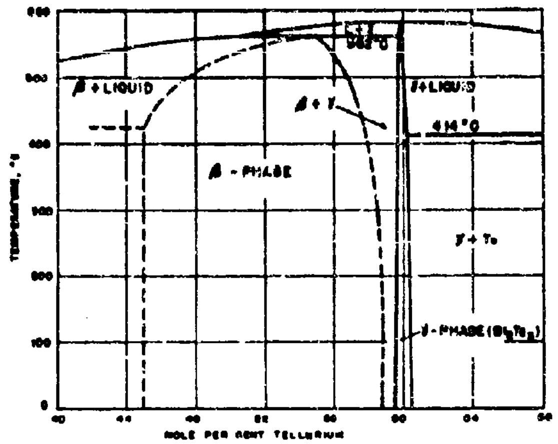
The ternary comprises a continuous series of isomorphic (rhombohedral) compounds [Ref. 19825]. As the selenium content increases, it becomes more difficult to obtain single crystal material in thin enough specimens to do optical work [Ref. 22468].

Composition	Symmetry	Lattice Constants a_o	c_o	c_o/a_o	Remarks	Ref.
Bi_2Te_3	hexagonal	4.384 ± 0.001Å	30.495 ± 0.006Å		300°K	21735
		a_o	c_o	c_o/a_o		
Bi_2Te_3	hexagonal	4.240	11.076	2.612		Donnay
		4.376	30.39	6.945		
		4.369	30.424	6.963		
		4.35	30.3	6.9655		
Bi_2Te_3	rhombohedral cell	10.473		α 24° 10'		Wyckoff*
	hexagonal cell	4.3835	30.487			
BiTe	cubic	6.47				Wyckoff**
Bi_2Se_3	hexagonal	6.702	11.26	1.680		
		4.15	28.65	6.8836	natural crystal isotypic with Bi_2Te_3	Donnay
		4.125	28.56	6.9236		
		4.13 to 4.16	28.7 to 29.3	6.9492 to 7.0096	variable composition	
Bi_2Se_3	rhombohedral cell	9.841		α 24° 16'		Wyckoff*
	hexagonal cell	4.138	28.64			
Bi_3Se_4	hexagonal	4.21 to 4.28	40.3 to 41.1	9.5724 to 9.6028	variable composition	Donnay
Bi_3Se_4	rhombohedral	13.719		α 17° 44'		Wyckoff*
	hexagonal cell	4.23	40.5			

Composition	Symmetry	Lattice Constants			Remarks	Ref.
BiSe	cubic	5.86				Donnay
BiSe	cubic	5.99				Wyckoff**
Bi_2Te_2Se	rhombohedral cell	10.255		24° 5'		Wyckoff*
	hexagonal cell	4.28	29.86			

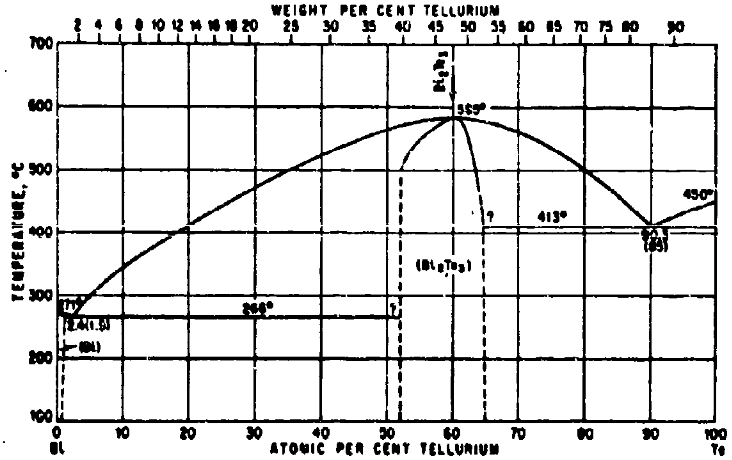
Molecular %		
Bi_2Te_3	Bi_2Se_3	Formula
100	0	Bi_2Te_3
95	5	$Bi_2Te_{2.85}Se_{0.15}$
90	10	$Bi_2Te_{2.7}Se_{0.3}$
83.33	16.67	$Bi_2Te_{2.5}Se_{0.5}$
80	20	$Bi_2Te_{2.4}Se_{0.6}$
66.67	33.33	Bi_2Te_2Se
60	40	$Bi_2Te_{1.8}Se_{1.2}$
50	50	$Bi_2Te_{1.5}Se_{1.5}$
40	60	$Bi_2Te_{1.2}Se_{1.8}$
33.33	66.67	Bi_2TeSe_2
22.22	77.78	$Bi_2Te_{0.77}Se_{2.33}$
0	100	Bi_2Se_3

The atomic formulas and corresponding molecular percent compositions are given here for general reference purposes.



Phase diagram of the bismuth-tellurium system in the region near the congruent melting compound.

[Ref. 21735]



Bi-Bi_2Te_3 eutectic, 1-1.5% wgt. Te, 263-267°C

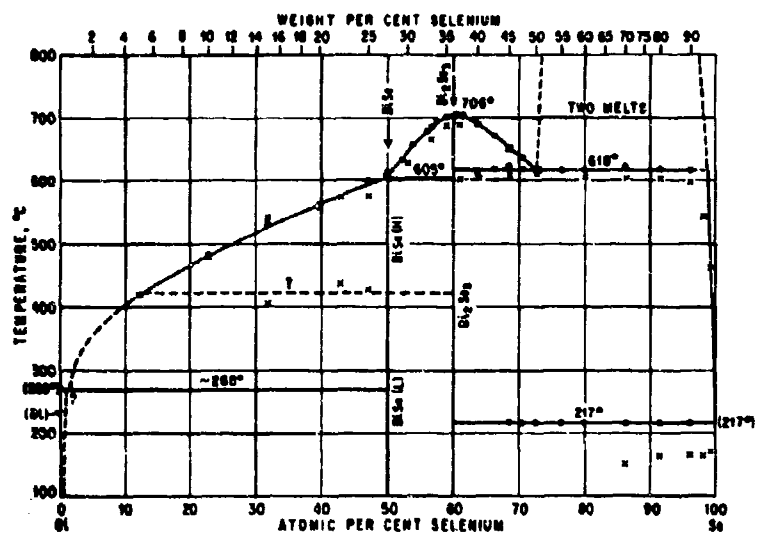
Bi_2Te_3 mpt = 583-586°C

Bi_2Te_3-Te eutectic 85 wgt.%, 410-413°C

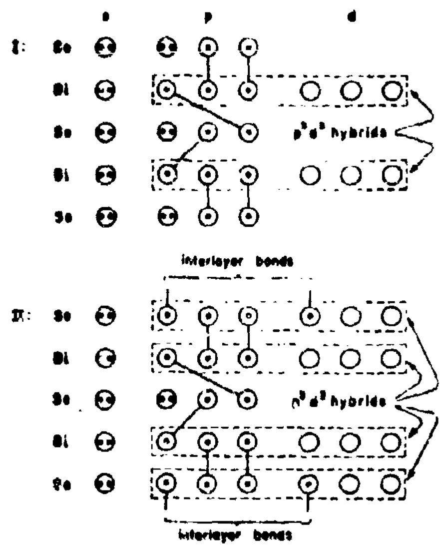
Bi mpt 269-271°C

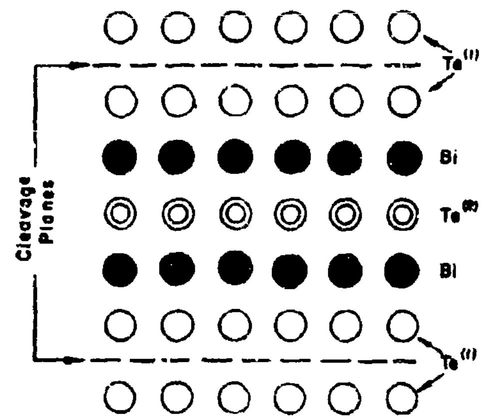
Te " 447-452°C

[Hansen]



Phase diagram of bismuth-selenium system [Hansen]





Arrangement of atoms in bismuth telluride as viewed parallel to basal plane, showing layer structure and two types of tellurium atoms.

[Ref. 19825]

Arrangement of atoms in bismuth selenide as viewed parallel to the basal (cleavage) plane.

[Ref. 5564]

"Considering the transition from Bi_2Te_3 to Bi_2Se_3 in light of the preferential-substitution hypothesis, Bi_2Te_3 has the highest p-type conductivity in the system. Then, with initial substitution of selenium in Te^2 sites, $Bi\text{-}Te^2$ pair bonds would be replaced by more ionic $Bi\text{-}Se^2$ bonds. Here decreasing electrical conductivity and increasing energy gap were noted. At $x = 1$, the $Bi\text{-}Te^2$ pair bonds hypothetically would be replaced by $Bi\text{-}Se^2$ bonds and the solid would consist of mutually-bonded $Te^1\text{-}Bi\text{-}Se^2\text{-}Bi\text{-}Te^1$ chains. At Bi_2Te_2Se the Seebeck coefficient is observed to cross zero, electrical conductivity is minimum and energy gap is essentially maximum. With continued selenium substitution (now in Te^1 sites) the observed property trends are reversed, i.e., the sign of the Seebeck coefficient becomes negative, electrical conductivity increases, and energy gap decreases slightly."

[Ref. 19825]

Stoichiometric bismuth telluride, Bi_2Te_3, is always p-type; excess tellurium or halogens yield n-type. Excess bismuth, lead or cadmium maintain the p-type. [Ref. 15291] Copper has a high diffusion rate in both the telluride and selenide and yields n-type material, so it should never be used for contacts. [Ref. 2595]

In the mixed crystals $Bi_2Te_{3-x}Se_x$, the carrier concentration decreases with increasing x-values, probably due to decrease in bismuth. Intrinsic conductivity occurs around Bi_2Te_2Se. At $x > 1$, the crystals are n-type, and the electron concentration then increases to a maximum of 3×10^{19}/cc for Bi_2Se_3. [Ref. 10984]

The thermoelectric properties of the bismuth telluride-bismuth selenide system are a function of the composition and the doping. Bismuth telluride-rich mixed crystals in this series are p-type if undoped. By means of donors such as silver, copper, chlorine, bromine and iodine, however, n-conduction can be achieved. This provides the optimum electron conductivity. Halogen donors are located in lattice vacancies, while copper and silver are held interstitially. Because of its high diffusion rate, under certain conditions, copper can cause ageing phenomena.

While normal electron scattering resulting from lattice vibrations is temperature dependent, the substitution of selenium for tellurium reduces the additional scattering due to lattice defects. At low temperatures, the scattering becomes evident on ionized centres. The highest figure of merit at room temperature, connected with the most favourable temperature range for the application of the Peltier method, is the 90-10 mixture prepared with optimum halogen doping.

Decreased figure of merit values for the n-type at low temperatures is connected with lowered thermal emf, but increased electrical and thermal conductivity. Thermal lattice scattering and nondegeneracy aside, at 20°C, the lattice portion of the thermal conductivity is .0109 W/cm deg. This value closely approaches the minimum of the lattice thermal conductivity nominally at about 20 mole percent bismuth selenide. If it is wished to displace the figure of merit maximum towards a higher temperature, the selenide portion may be increased in order to increase the energy gap. Strong doping also allows intrinsic conduction to occur only at higher temperatures. Both methods, however, produce a decrease in the maximum figure of merit.

WYCKOFF, R.* CRYSTAL STRUCTURES. 2nd. ed. N.Y., Interscience Publishers, 1963. V. 2, p. 29-30.

WYCKOFF, R.** CRYSTAL STRUCTURES. 2nd. ed. N.Y., Interscience Publishers, 1963. V. 1, p. 86.

DONNAY, J.D.H. CRYSTAL DATA. DETERMINATIVE TABLES. 2nd. ed. American Crystallography Association, 1963.

HANSEN, M. CONSTITUTION OF BINARY ALLOYS. 2nd. ed., prepared with the cooperation of ANDERKO, K. N.Y., McGraw-Hill, 1958. p. 335 and 340.

BISMUTH TELLURIDE

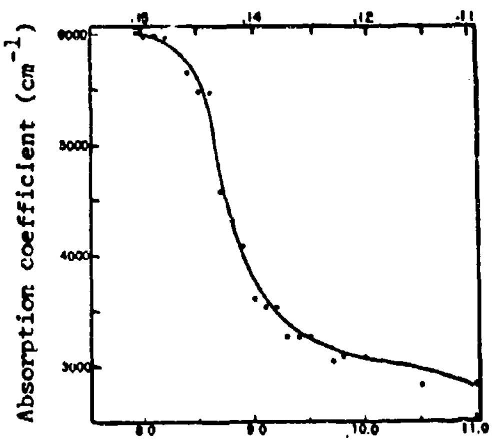
ABSORPTION (α)

Absorption coefficient in single crystal Bi_2Te_3 as a function of wavelength at 300°K. Measurements on (0001) cleavage plane.

$n = 5x10^{17}$/cc at 300°K.

ρ = .055 ohm-cm.

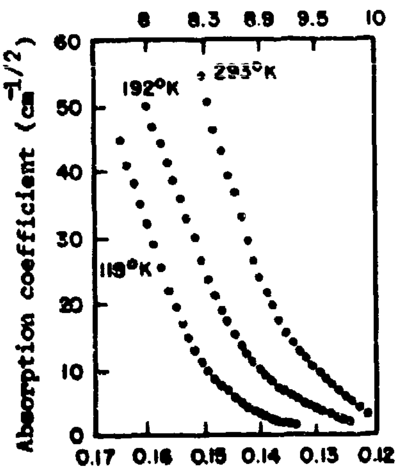
Photon energy (eV)



Wavelength (microns)

[Ref. 10535]

Wavelength (microns)



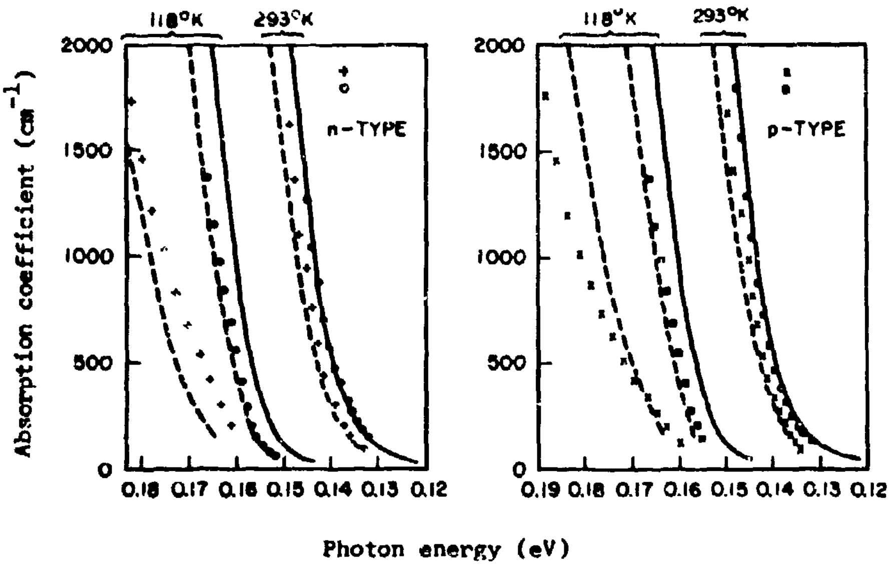
Photon energy (eV)

Absorption edge data for single crystal, n-type, Bi_2Te_3, shown by the square root of the absorption coefficient as a function of photon energy. Curves are calculated from transmission measurements made at three temperatures on a nearly intrinsic sample, iodine-compensated, on the (0001) cleavage plane.

[Ref. 3124]

BISMUTH TELLURIDE

ABSORPTION



A comparison between the measured and calculated absorption edges in single crystal, n- and p-type, Bi_2Te_3 samples, showing the effects of degeneracy at 2 temperatures.

—— absorption edges, at two temperatures, for the single crystal, n-type, intrinsic sample shown on preceding page, given here for comparison.

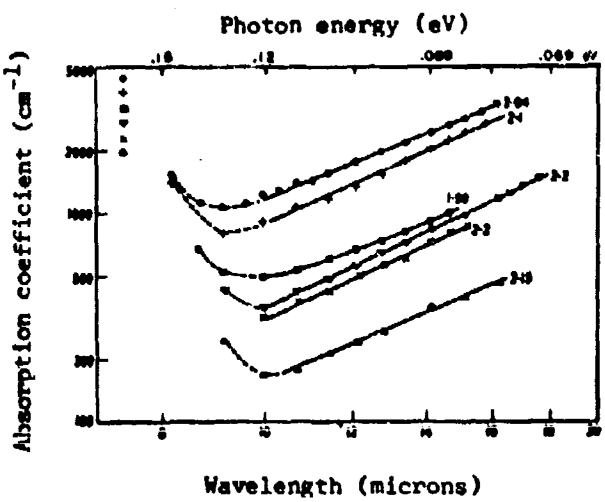
---- calculated edges showing effects of degeneracy at 118 and 292°K.

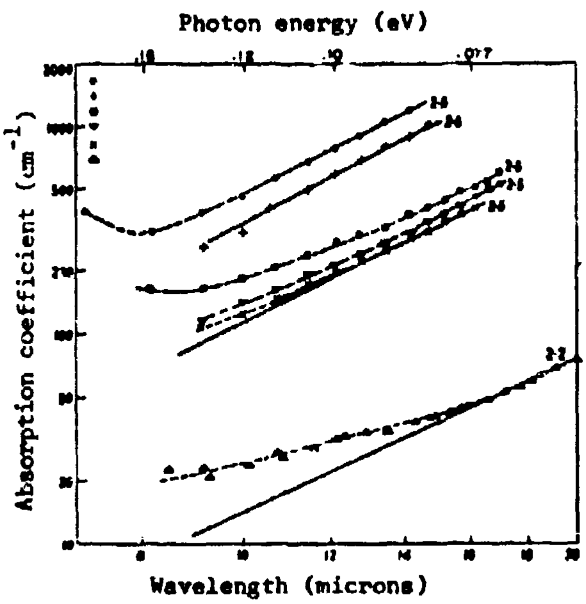
Points show experimental data

[Ref. 3124]

BISMUTH TELLURIDE

ABSORPTION





Free carrier absorption in single crystal Bi_2Te_3 at 300°K. Values are calculated from transmission measurements on (0001) cleavage plane. Absorption coefficient, $\alpha \sim \lambda^s$. Values of s are shown on curves, by solid lines.

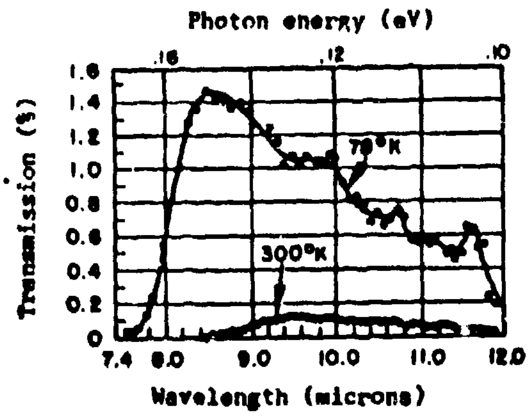
	p-type		n-type
	carrier concentration n, at 4°K		
+	3.5×10^{18}/cc	o	1.3×10^{19}/cc
▽	2.1×10^{18}	□	3.8×10^{18}
x	1.7×10^{18}		
△	1.7×10^{17} (intrinsic)		

[Ref. 524]

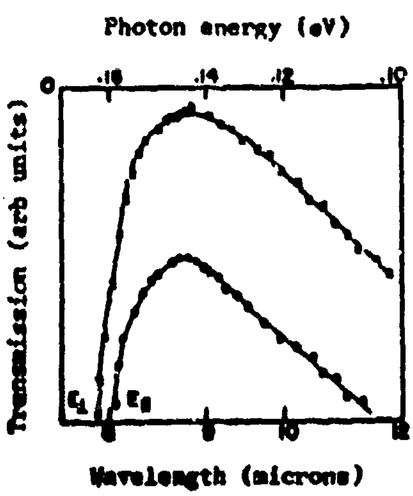
BISMUTH TELLURIDE

ABSORPTION

Infrared transmission as a function of wavelength for highly purified, p-type single crystal Bi_2Te_3 at two temperatures. Thickness was 0.06 mm and illumination was normal to the cleavage plane (0001).



[Ref. 2866]



Transmission as a function of wavelength for single crystal, n-type Bi_2Te_3 at 118°K, using light polarized in the two principal directions. The sample is iodine compensated-intrinsic.

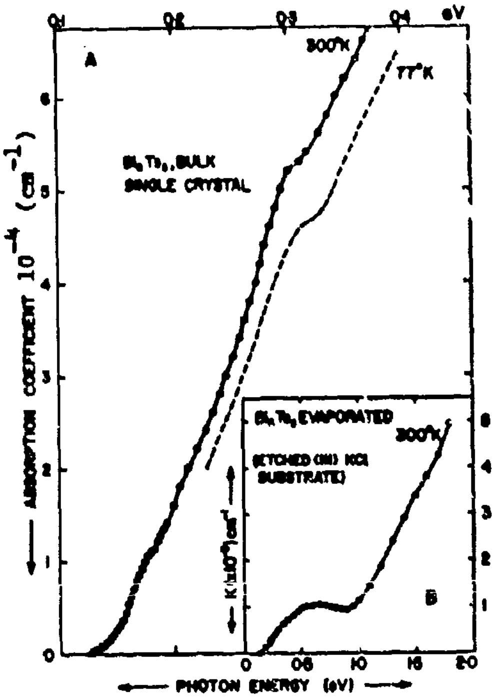
$E_\parallel$, polarized light parallel to cleavage planes;

$E_\perp$, polarized light perpendicular to cleavage planes, (0001).

[Ref. 312*]

BISMUTH TELLURIDE

ABSORPTION



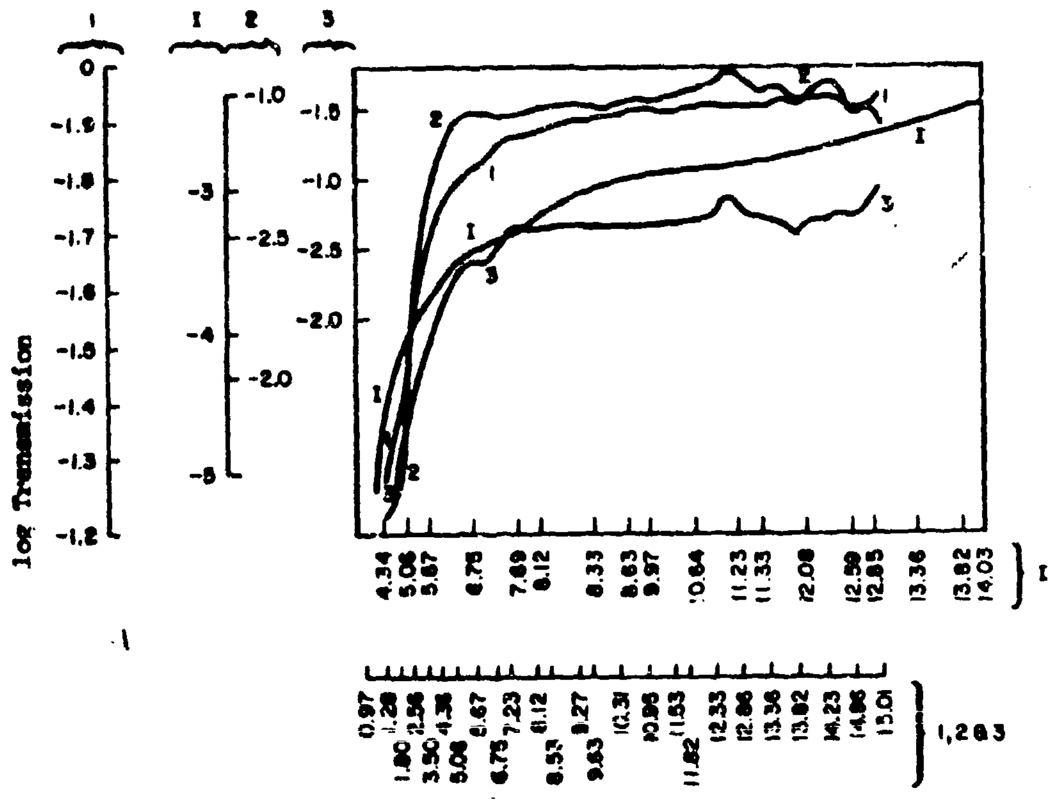
Absorption coefficient as a function of photon energy for single crystal, (A) and film (B) Bi_2Te_3, deposited on the (111) plane of a KCl substrate.

The single crystal shows a direct interband transition at 0.18 eV and a higher transition at 0.3 eV.

[Ref. 22468]

BISMUTH TELLURIDE

ABSORPTION



Transmission as a function of wavelength for:

I. Single crystal, thin section, p-type Bi_2Te_3

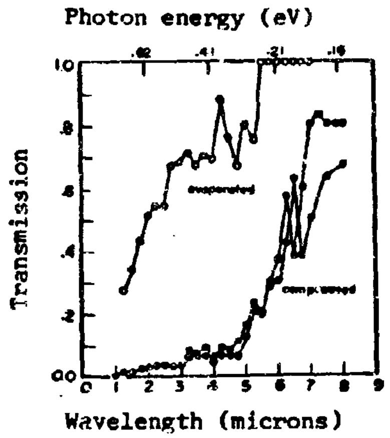
1, 2, 3. Thin evaporated films of p-type Bi_2Te_3

[Ref. 2711]

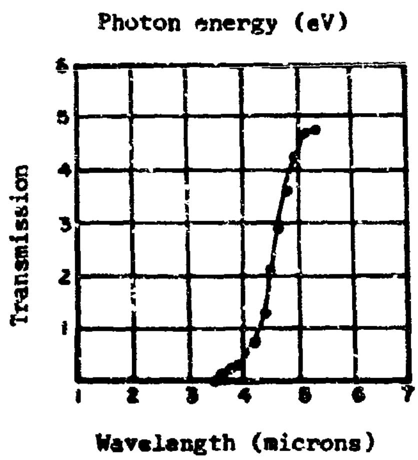
BISMUTH SELENIDE

ABSORPTION

Transmission as a function of wavelength for films and pressed powder disks of n-type Bi_2Se_3 at 300°K.



[Ref. 3097]



Transmission as a function of wavelength for purified single crystal, n-type Bi_2Se_3 at 300°K. Illumination normal to the cleavage plane (0001), of a 0.03 mm thick sample. Carrier concentration is 2×10^{19}/cc.

[Ref. 2866]

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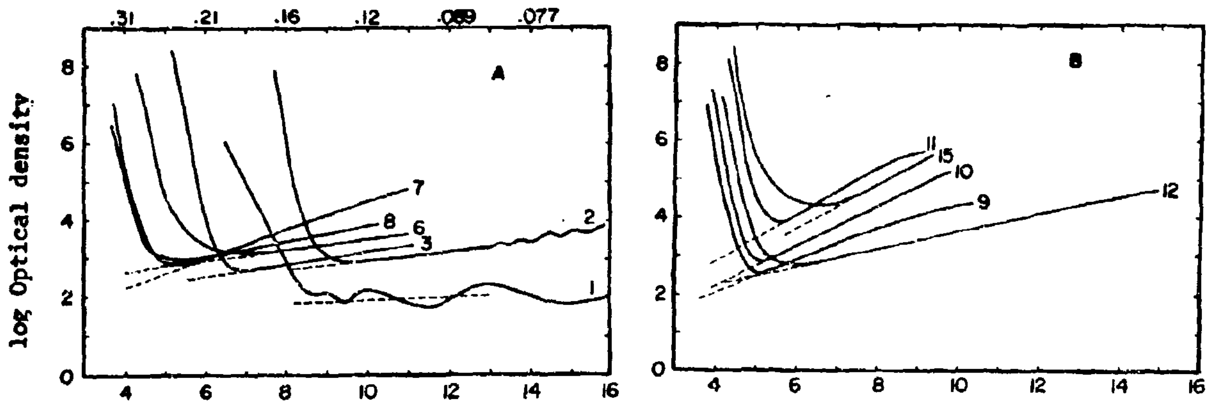
BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

ABSORPTION



Optical density (normalized transmission) for Bi_2Te_3-Bi_2Se_3 polycrystalline, (plane parallel) samples at 300°K. Sample specifications given in table. Curves 1 and 2 for pure Bi_2Te_3 show transmission interference fringes.

Sample (single crystal)	Bi_2Te_3	Bi_2Se_3	Type	Thickness (microns)
1	100	-	p	3
2	100	-	p	17
3	90	10	p	20
6	80	20	p	30
7	70	30	n	40
8	66.7	33.3		21
9	60	40		38
10	50	50		29
11	40	60		39
12	30	70		21
15	-	100		25

[Ref. 22468]

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

DEBYE TEMPERATURE (θ_D)

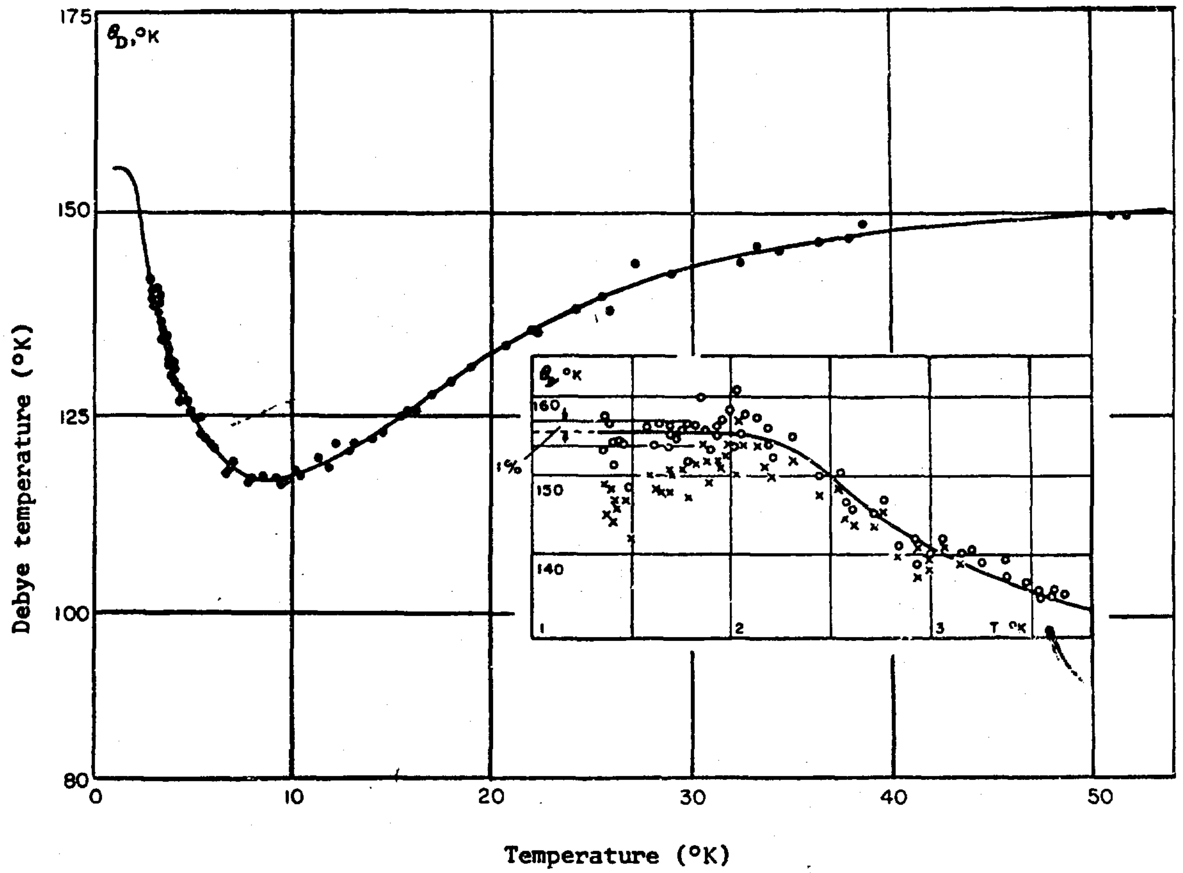
$\theta_{s.h.}$	$\theta_{t.c.}$	T°K	Sample Bi_2Te_3	Ref.
155.5 ± 3		0	macrocrystalline	7764
161		80	polycrystalline	3030
158		90		
159		100		
161		120		
165		140		
171		160		
182		180		
190		200		
212		220		3030
117	71.6	10	single crystal, n-, and p-type	3466
127.5	79.3	15		
142	88.5	20		
	95.3	25		
	98.2	30		3466
			Bi_2Se_3	
180		80	polycrystalline	3030

$\theta_{t.c.}$ is calculated from thermal conductivity data

$\theta_{s.h.}$ is calculated from specific heat data

BISMUTH TELLURIDE

DEBYE TEMPERATURE



Characteristic Debye temperature for macrocrystalline, p-type Bi_2Te_3 between 1.37 and 50°K, derived from the experimental heat capacity data. The region below 3.5°K is shown separately and corresponds to the portion of the main figure which has no points. The crosses indicate values calculated on the assumption that the entire measured heat capacity is due to the lattice.

[Ref. 7764]

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BISMUTH TELLURIDE

DIELECTRIC CONSTANT (ε)

Symbol	Value	Sample	Wavelength	Temperature	Ref.
ε_o	∿ 100 (est.)	single crystal, n-type $n = 3x10^{17}-6x10^{19}/cc$			14854
ε_∞	84.6	single crystal, n-type nearly intrinsic, calc. from index of refraction n = 9.2	8 to 14μ	118°K	3124

Thorough search of the literature indicates no successful measurements have been made for dielectric constant or refractive index of bismuth selenide.

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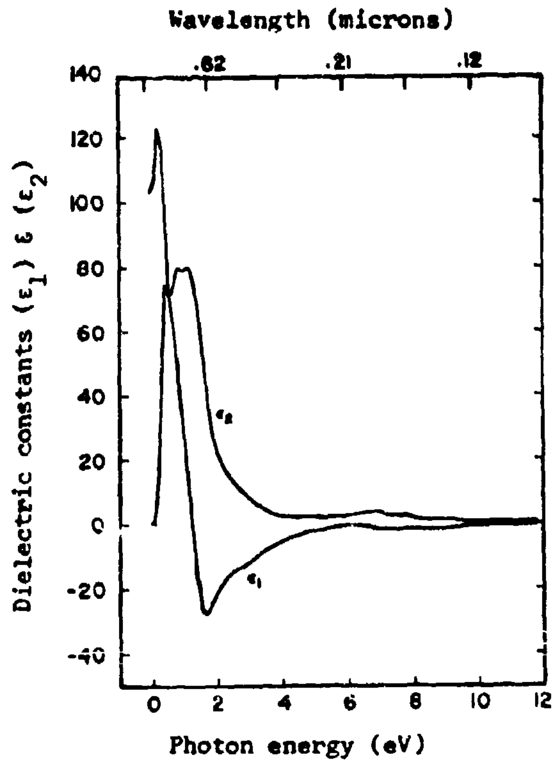
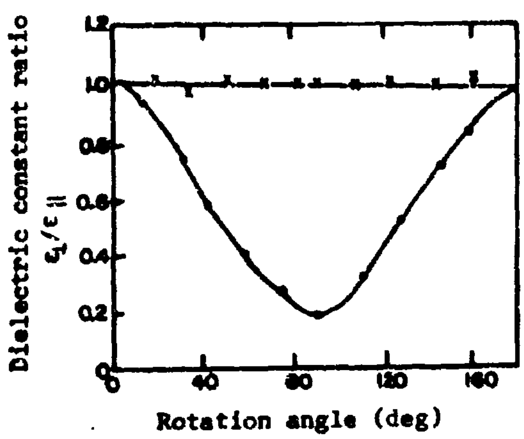
BISMUTH TELLURIDE

DIELECTRIC CONSTANT



Real and imaginary part of the dielectric constant ϵ_1 and ϵ_2, as a function of photon energy in single crystal, p-type Bi_2Te_3. Radiation normal to the cleavage plane (0001) $E_{\perp c}$. Values calculated from reflectivity measurements.

[Ref. 22468]



Anisotropy of dielectric constant in single crystal Bi_2Te_3.

x is $\epsilon_{\parallel}/\epsilon_{\parallel}$

• is $\epsilon_{\perp}/\epsilon_{\parallel}$

$\epsilon_{\parallel}$ is dielectric constant measured parallel to c-axis or (0001)

$\epsilon_{\perp}$ is dielectric constant measured normal to (0001)

[Ref. 10299]

BISMUTH TELLURIDE

EFFECTIVE MASS (m*)

Symbol	Value	Sample	Test Measurement	Temperature	Ref.
m_1	.0505	single crystal, p-type	magnetoelectric	300°K	18204
m_2	.209				
m_3	.386				18204
m_{c_1} †	0.114	single crystal	magnetoelectric at 110 kOe	2, 4, and 77°K	9763
m_{c_2}	0.145				
m_{c_3}	0.236				9763
m_c †	0.13	single crystal, p-type $n \sim 10^{18}$/cc, field parallel (0001)	deHaas-vanAlphen oscillations to 190 kG	1.4-4.2°K	11903

Faraday rotation at 17 kOe and λ = 8-15μ and 78°K	Optical absorption at λ = 8-20μ, made at 300°K	n, cm^{-3}	Single crystal type	Ref.
0.26	-	1.5×10^{19}	p	524
-	0.35	1.3×10^{19}	p	
0.25	0.28	3.8×10^{18}	p	
0.15	0.15	1.7×10^{18}	n, I-compensated	
-	0.16	2.1×10^{18}	n	
0.14	0.13	3.5×10^{18}	n	524

Field parallel (0001) λ normal (0001)

† m_c = cyclotron effective mass

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BISMUTH TELLURIDE

EFFECTIVE MASS

Symbol	Value	Sample	Test Measurement	Temperature	Ref.
m_n	0.32	single crystal, n-type, iodine and tellurium-doped	thermal emf	300°K	2624
m_p	0.46	single crystal, p-type, bismuth and lead-doped			2624
m_{DS}	0.511	single crystal, $n_p = 6 \times 10^{18}$/cc	Hall	280°K	9763
m_{DS}	0.511	single crystal, p-type, $n = 3 \times 10^{18}$/cc	Hall	77°K	3207
m_{DS}	0.055 (lower conduction band)	single crystal, n-type Te-doped, $n = 2.4 \times 10^{17}$/cc	thermal emf	4.2°K	14854

m_{DS} = density of states effective mass

Symbol	Value	Sample	Test Measurement	Temperature	Ref.
m_n	1.07	single crystal, p-type, normal to c-axis, $n = 1.4 \times 10^{19}$/cc	electrical & thermal emf	100-700°K	407
m_p	1.26		4 kG field		407
m_p	1.46	polycrystalline, p-type, $n = 4 \times 10^{19}$/cc	Hall coefficient and specific heat	2°K	7764

These excessively high effective mass values are due in part to channeling in a polycrystalline sample, but even more to neglect of the anisotropy factor in the electromagnetic measurements. The present interpretation of a six-valley band structure would reduce these high values by a factor of 3 with the introduction of the tensor components.

BISMUTH SELENIDE

EFFECTIVE MASS

Symbol	Value	Sample	Test Measurement	Temperature	Ref.
m_n	0.18	polycrystalline	Hall	300°K	2473
m_n	0.18	polycrystalline, n-type, $n = 6.7 \times 10^{17}$ and 3×10^{18}/cc	thermal emf	100°K	21372
m_n	0.16	polycrystalline, n-type, $n = 4.2 \times 10^{18}$ and 5.4×10^{18}/cc	thermal emf	100°K	21372
m	~ 0.4 (calc.)	macrocrystalline, n-type, $n = 10^{19}$/cc	electrical	300°K	2538
m_2/m_1	0.33	single crystal, n-type (0001) cleavage plane	magnetoelectric	90°K	3350
m_3/m_1	4.2	↓	↓	↓	↓
$m_1:m_2:m_3$	(1.0:0.33:4.2)				3350

Bi_2Te_3

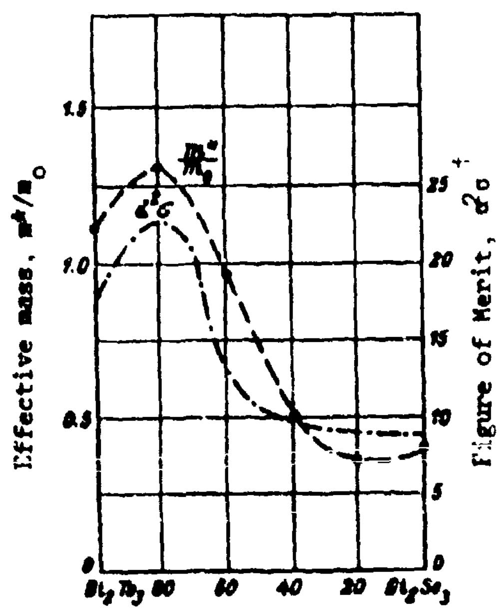
Symbol	Value	Sample	Test Measurement	Temperature	Ref.
m_1/m_2	1.21	single crystal, n-type	magnetoelectric	77°K	2360
m_3/m_2	0.093	↓	↓	↓	↓
$m_1:m_2:m_3$	(1.0:0.83:.077)				2360

80% Bi_2Te_3-20% Bi_2Se_3

Symbol	Value	Sample	Test Measurement	Temperature	Ref.
m_n	1.1	polycrystalline, $n = 3 \times 10^{19}$/cc	thermal emf	77-630°K	14600
m^*	1.3	macrocrystalline, n-type, I-doped	thermal emf	300°K	2538

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

EFFECTIVE MASS



Effective mass as a function of composition for macrocrystalline, iodine-doped samples in the Bi_2Te_3-Bi_2Se_3 system at 300°K. Figure of merit measurements for same samples are shown.

† Usual figure of merit is defined as $\frac{\alpha^2\sigma}{k}$

[Ref. 2538]

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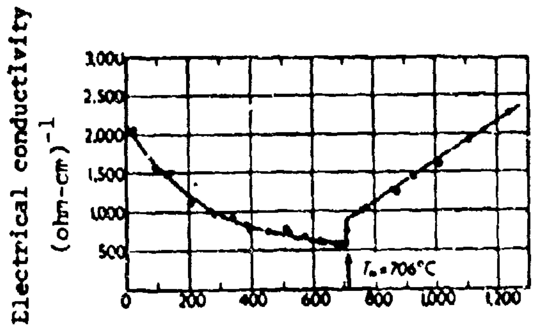
BISMUTH TELLURIDE-BISMUTH SELENIDE

ELECTRICAL CONDUCTIVITY (σ)

[Additional conductivity curves will be found in THERMOELECTRIC PROPERTIES Section]

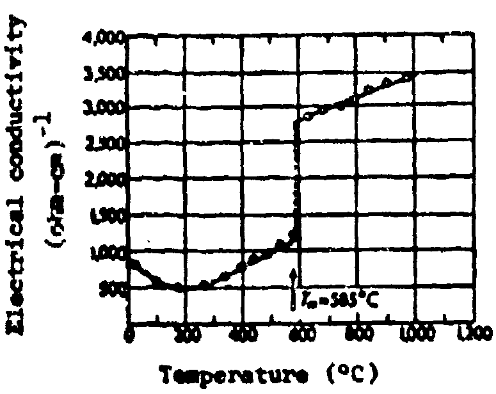
Temperature dependence of the electrical conductivity of stoichiometric Bi_2Se_3 in the solid and liquid states.



[Ref. 3528]

Both solid and liquid Bi_2Te_3 and Bi_2Se_3 are semiconductors, but on fusion they show metallic type conductivity.

t_m = melting point



Temperature dependence of the electrical conductivity of stoichiometric Bi_2Te_3 in the solid and liquid states.

[Ref. 3528]

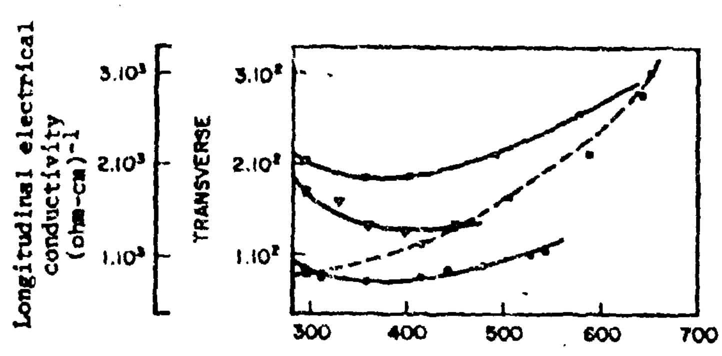
BISMUTH TELLURIDE

ELECTRICAL CONDUCTIVITY

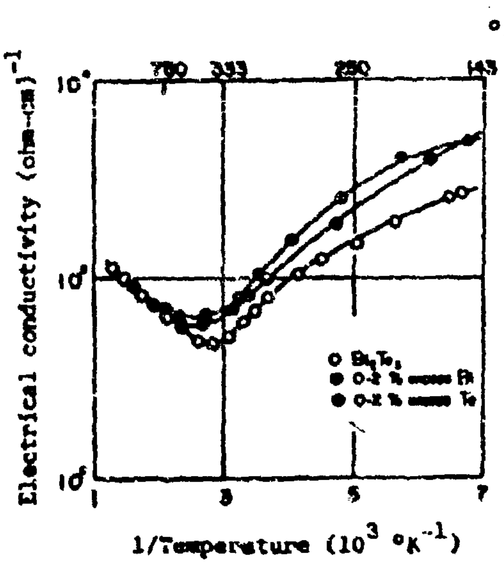
Temperature dependence of electrical conductivity as a function of temperature for single crystal, n-type Bi_2Te_3. $n \sim 10^{19}$/cc for three similar samples. Conductivity normal to (0001) is about 0.1 of the parallel conductivity.

—— parallel to cleavage plane (0001)

- - - normal to cleavage plane (0001)



[Ref. 631]



Electrical conductivity as a function of reciprocal temperature for single crystal, p-type Bi_2Te_3 cut on the (0001) cleavage plane.

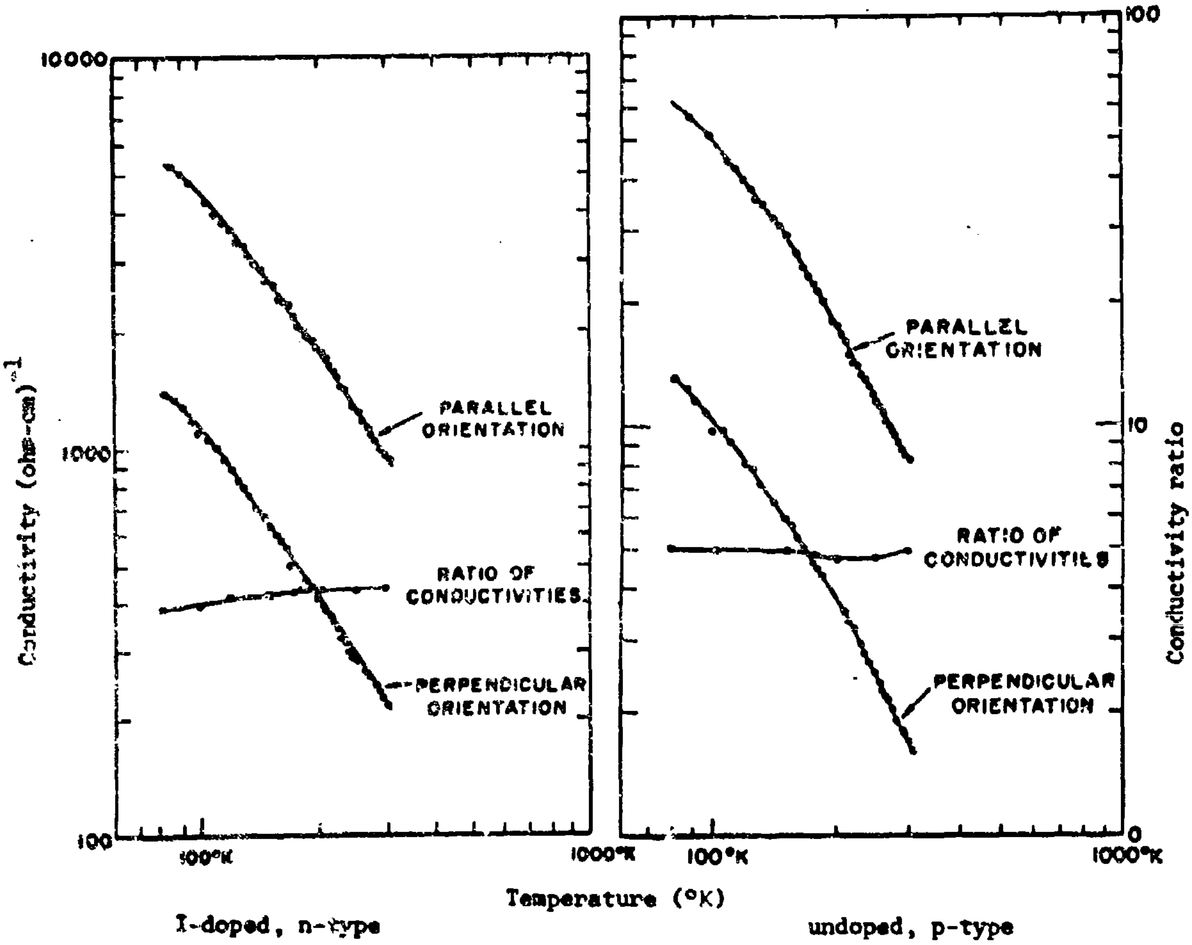
o Stoichiometric Bi_2Te_3, $n = 1.4 \times 10^{19}$/cc.

Purified Bi and Te were used.

[Ref. 407]

BISMUTH TELLURIDE

ELECTRICAL CONDUCTIVITY

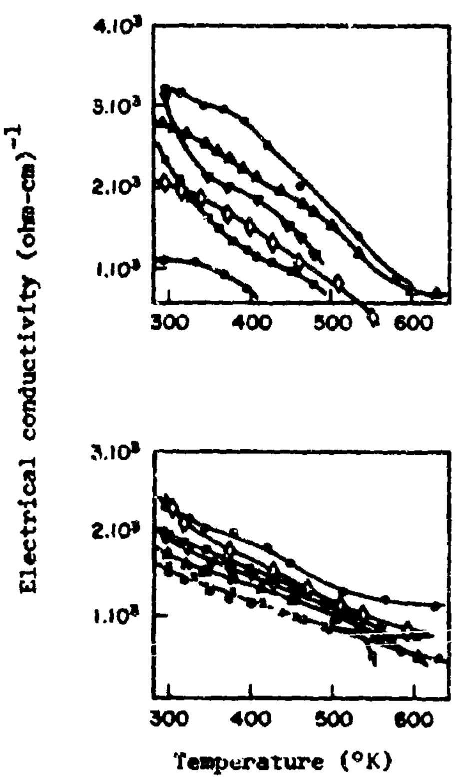


Conductivity and conductivity ratio of two types of single crystal Bi_2Te_3 as a function of temperature. Measurements are taken parallel and normal to (0001). The zero slope of the conductivity ratio in the undoped sample indicates a multiple carrier and lattice scattering mechanism at 300-700°K, whereas, the 0.25 slope in the iodine-doped sample from 100-300°K indicates anisotropy due to a single carrier and multiple scattering mechanism.

[Ref. 19827]

BISMUTH SELENIDE

ELECTRICAL CONDUCTIVITY



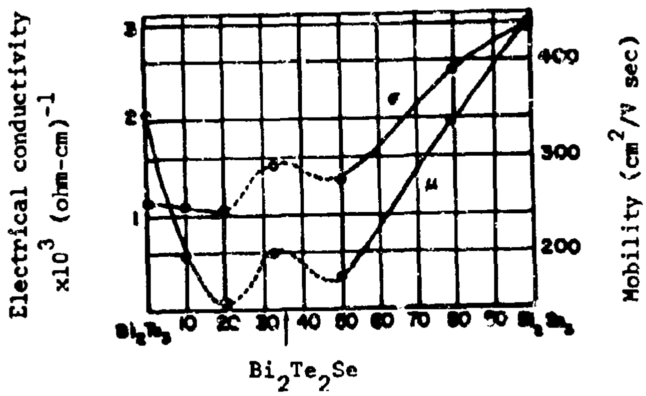
Electrical conductivity as a function of temperature for Bi_2Se_3 n-type, single crystals parallel to their cleavage plane, (0001). Carrier concentrations are not specified for individual samples, n $\sim$ $2x10^{19}$/cc. Conductivity normal to the cleavage plane is about 60 $(ohm\text{-}cm)^{-1}$ at 300°K or approximately 3% of the parallel conductivity.

[Ref. 630]

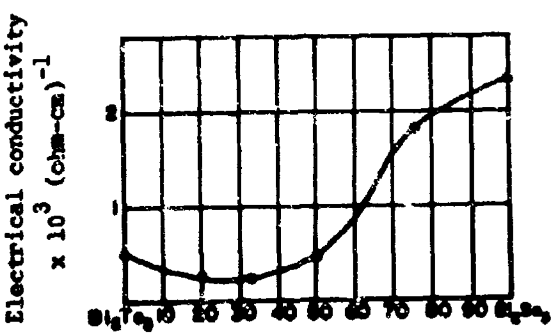
BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

ELECTRICAL CONDUCTIVITY

Electrical conductivity as a function of composition in silver iodide-doped, n-type, polycrystalline samples of the Bi_2Te_3-Bi_2Se_3 system at 300°K. The mixed crystals are homogeneous throughout, according to x-ray investigation, which shows a continuous decrease in the lattice constants with increase in selenium content.



[Ref. 3867]

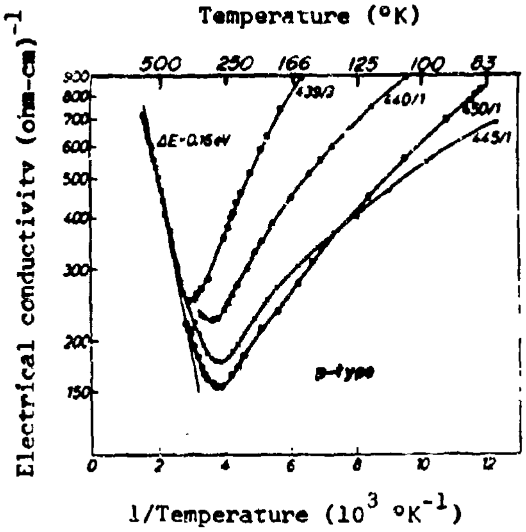


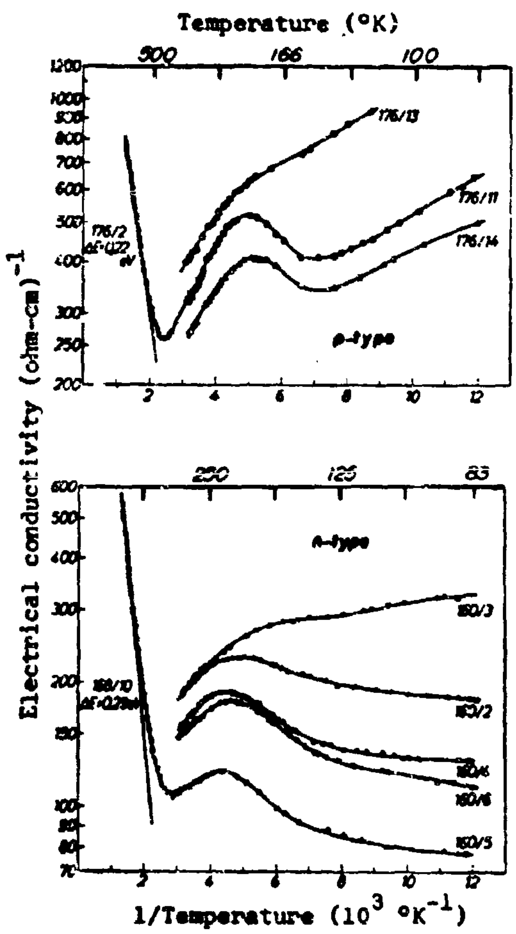
Electrical conductivity as a function of composition for macrocrystalline samples of $Bi_2Te_{3-x}Se_x$, undoped, at 300°K.

[Ref. 3867]

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

ELECTRICAL CONDUCTIVITY





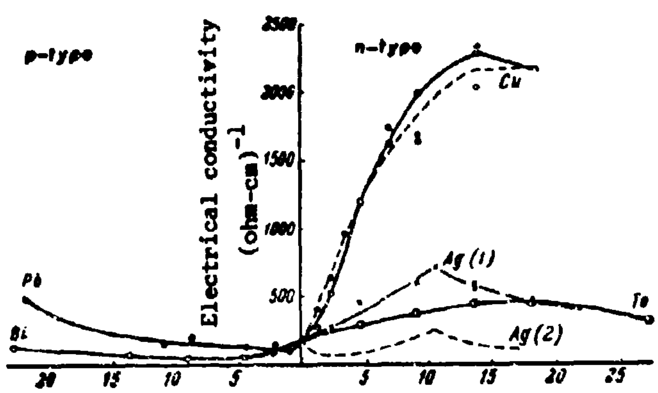
Electrical conductivity as a function of reciprocal temperature for three compositions all with low carrier concentrations which are obtained by compensation. Samples are single crystal, n-, and p-type, A) Bi_2Te_3; B) 90% Bi_2Te_3-10% Bi_2Se_3: and C) Bi_2Te_3Se.

Curves are identified by sample numbers, however, no definite specifications are given.

[Ref. 10984]

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

ELECTRICAL CONDUCTIVITY



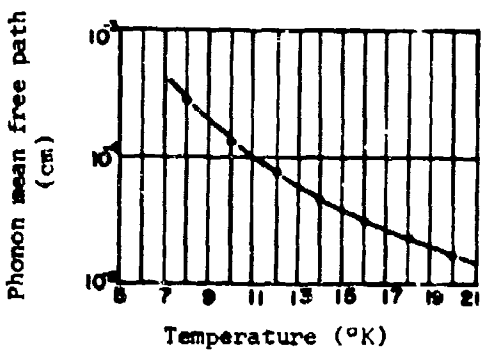
Electrical conductivity as a function of free element concentration for variously doped macrocrystalline samples of 80% Bi_2Te_3-20% Bi_2Se_3. Silver additions cause instability; Ag(2) was measured several months after Ag(1).

[Ref. 2538]

BISMUTH TELLURIDE

ELECTRICAL CONDUCTIVITY

Mean Free Path



Phonon mean free path as a function of temperature in single crystal n-, or p-type Bi_2Te_3, calculated from specific heat and thermal conductivity measurements.

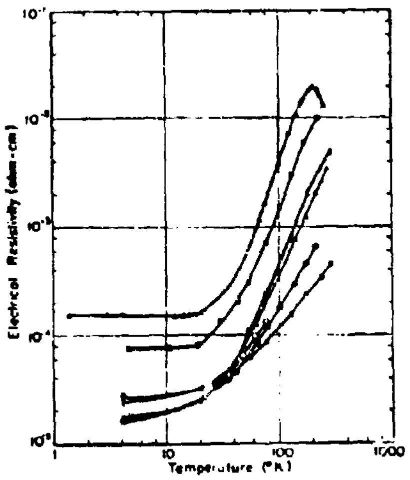
[Ref. 3466]

BISMUTH TELLURIDE

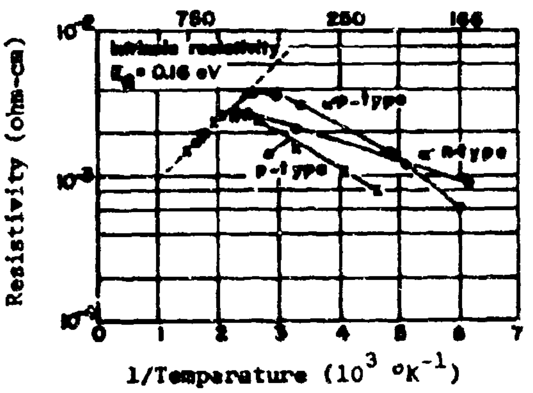
ELECTRICAL RESISTIVITY (ρ)

Electrical resistivity as a function of temperature for tellurium doped, n-type Bi_2Te_3, single crystal.

	n, cm^{-3}
Δ	2.4×10^{17}
□	5.3×10^{17}
▲	3.0×10^{18}
◊	3.4×10^{18}
o	-
●	1.2×10^{19}
■	6.8×10^{19}



[Ref. 14854]



Resistivity as a function of reciprocal temperature for one n-type, and two p-type specimens of Bi_2Te_3. The samples are single crystal, n-type have excess tellurium or iodine.

$$n_p = 8\times10^{18}/cc \text{ at } 300°K$$

p-type are bismuth or lead-doped

$$n_n = 5\times10^{18}/cc \text{ at } 300°K.$$

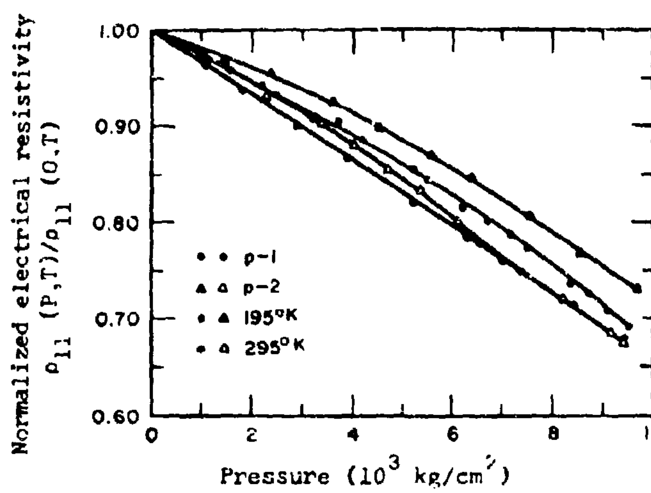
[Ref. 2624]

BISMUTH TELLURIDE

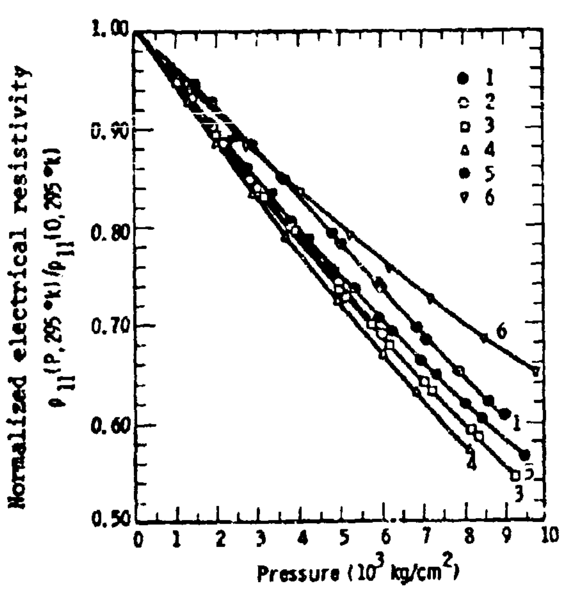
ELECTRICAL RESISTIVITY

Normalized electrical resistivity as a function of pressure for two single crystal, p-type, Te-doped Bi_2Te_3 samples at two temperatures. Current normal to the rotation axis and parallel to (0001).

T is given temperature
P is pressure
0 is zero pressure



[Ref. 18361]



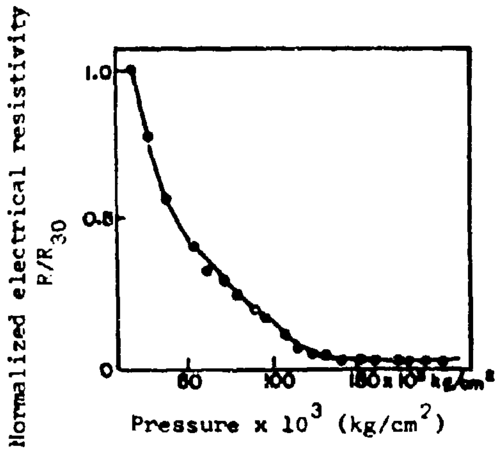
Normalized electrical resistivity as a function of pressure for single crystal, n-type, Te-doped Bi_2Te_3 at 295°K. Current normal to rotation axis, parallel to (0001). Carrier concentration is lowest for sample #1, and highest for #6.

[Ref. 18361]

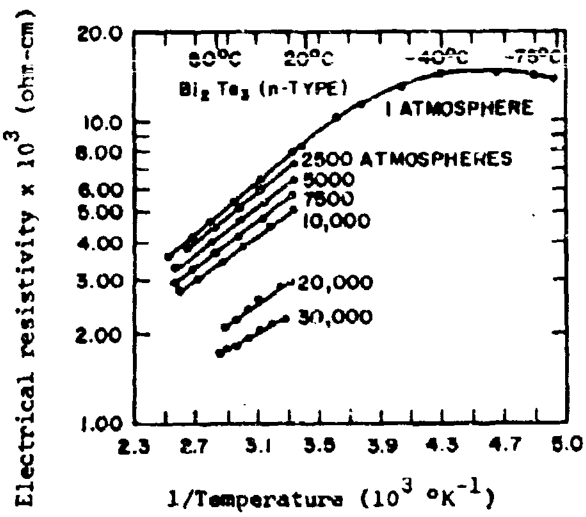
BISMUTH TELLURIDE

ELECTRICAL RESISTIVITY

Variation of a normalized electrical resistance of Bi_2Te_3 with pressure up to 200 000 atm at 300°K. R_{30} is electrical resistance at 25 600 kg/cm^2 and is taken as the initial resistance.



[Ref. 16009]



Resistivity as a function of reciprocal temperature for Bi_2Te_3 single crystal, from 1 to 30 000 atmospheres.

[Ref. 21112]

BISMUTH TELLURIDE

ELECTRICAL RESISTIVITY

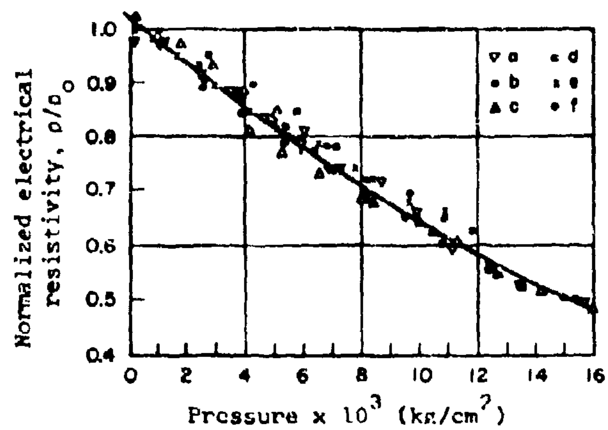
Effect of hydrostatic pressure on the normalized electrical resistivity of Bi_2Te_3 at 300°K.

a, b: sample I, p-type
c, d: sample II, p-type
e, f: 2 samples, n-type

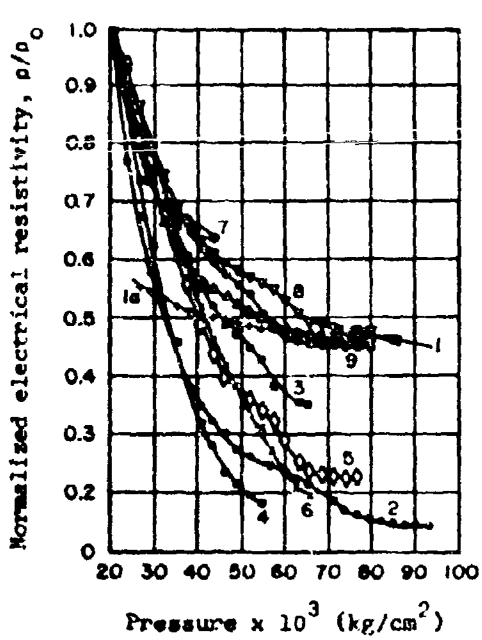
a, c, e, at increasing pressure
c, d, f, at decreasing pressure

Piezocoefficient of resistivity for 1 to 15×10^3 kg/cm².

$[1/R{:}\Delta R/\Delta P = 3.5 \times 10^{-5}/\text{kg cm}^{-2}]$.



[Ref. 16204]



Normalized electrical resistivity of single crystal Bi_2Te_3 as a function of hydrostatic pressures of 20-95 kg/cm² at 300°K.

1, 2: sample I, p-type
3, 4, 5, 6, 7: sample II, p-type
8, 9: 2 samples, n-type

All curves at increasing pressure, except 1a, at decreasing pressur .

[Ref. 16204]

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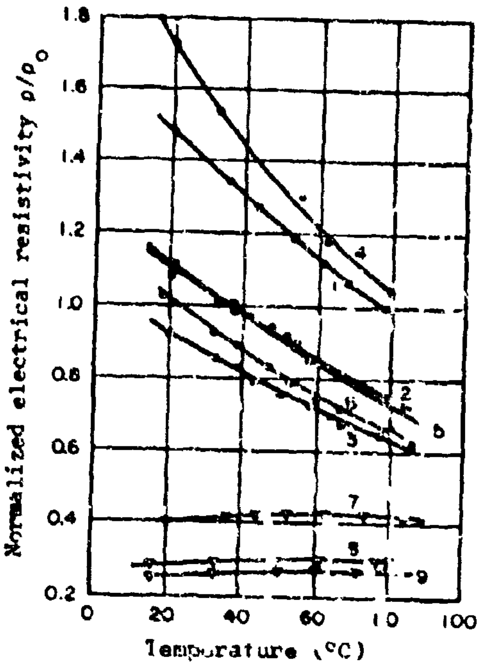
BISMUTH TELLURIDE

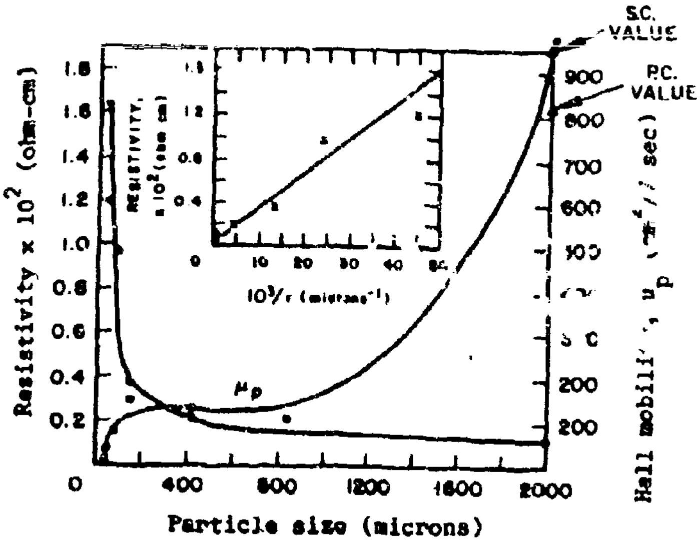
ELECTRICAL RESISTIVITY

Electrical resistivity of single crystal Bi_2Te_3 as a function of temperature at several constant hydrostatic pressures.

Sample	Type	Pressure (kg/cm^2)
1	p	atmospheric
2	p	5 870
3	p	10 365
4	p	atmospheric
5	p	8 340
6	p	11 150
7	n	atmospheric
8	n	8 290
9	n	11 650



[Ref. 16204]



Resistivity and Hall mobility of pressed Bi_2Te_3 powders as a function of grain size at 77°K. The powders are p-type, $n \sim 2x10^{19}/cc$.

S.C. is single crystal
P.C. is polycrystalline

r is $\frac{\text{grain boundary area}}{\text{grain boundary volume}}$

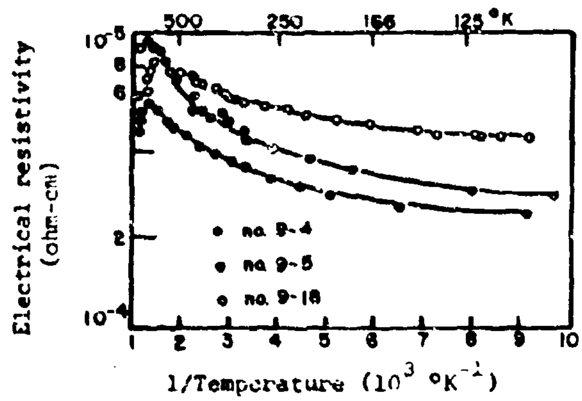
[Ref. 8758]

BISMUTH SELENIDE

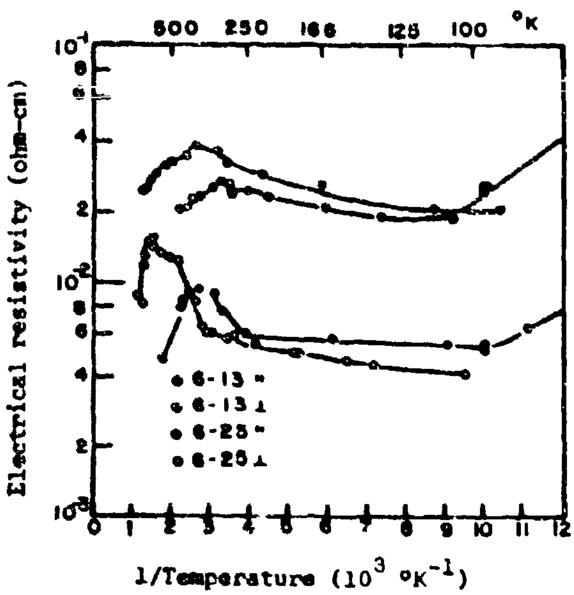
ELECTRICAL RESISTIVITY

Electrical resistivity as a function of reciprocal temperature for polycrystalline BiSe.

Sample	n, cm^{-3}
9-4	$2.0x10^{20}$
9-5	$2.5x10^{20}$
9-18	$2.2x10^{20}$



[Ref. 3097]



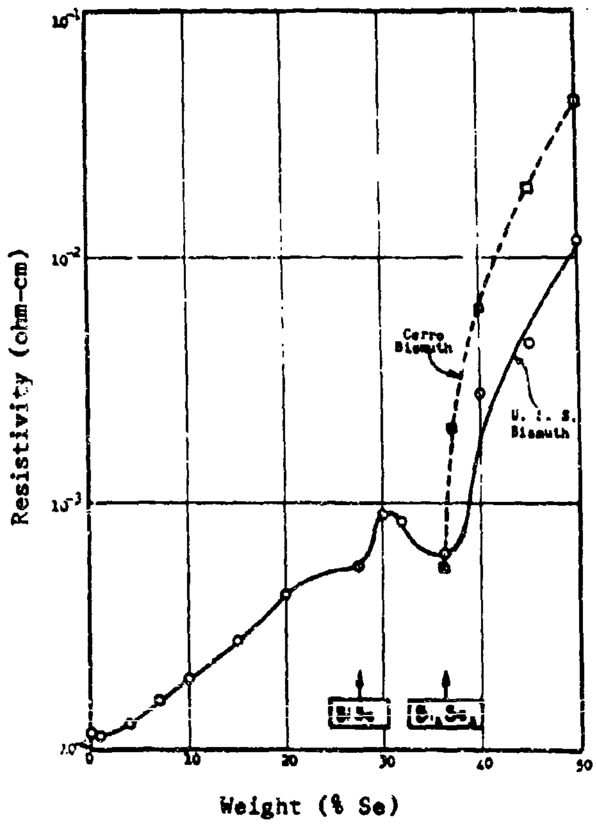
Electrical resistivity as a function of reciprocal temperature for single crystal Bi_2Se_3, (0001) cleavage plane.

Sample	n, cm^{-3}
6-13, parallel	$3.3x10^{18}$
6-13, normal	$2.5x10^{18}$
6-25, parallel	$2.30x10^{18}$
6-25, normal	$1.82x10^{18}$

[Ref. 3097]

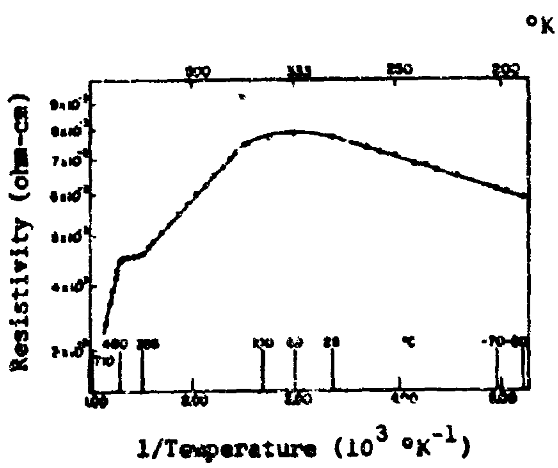
BISMUTH SELENIDE

ELECTRICAL RESISTIVITY



Electrical resistivity of BiSe alloys as a function of Se content at 300°K. The alloys were macrocrystalline. A high purity grade of selenium was used with two commercial grades of bismuth. The Cerro bismuth was purer than the U.S.S. brand, although the latter was purified before use.

[Ref. 12851]



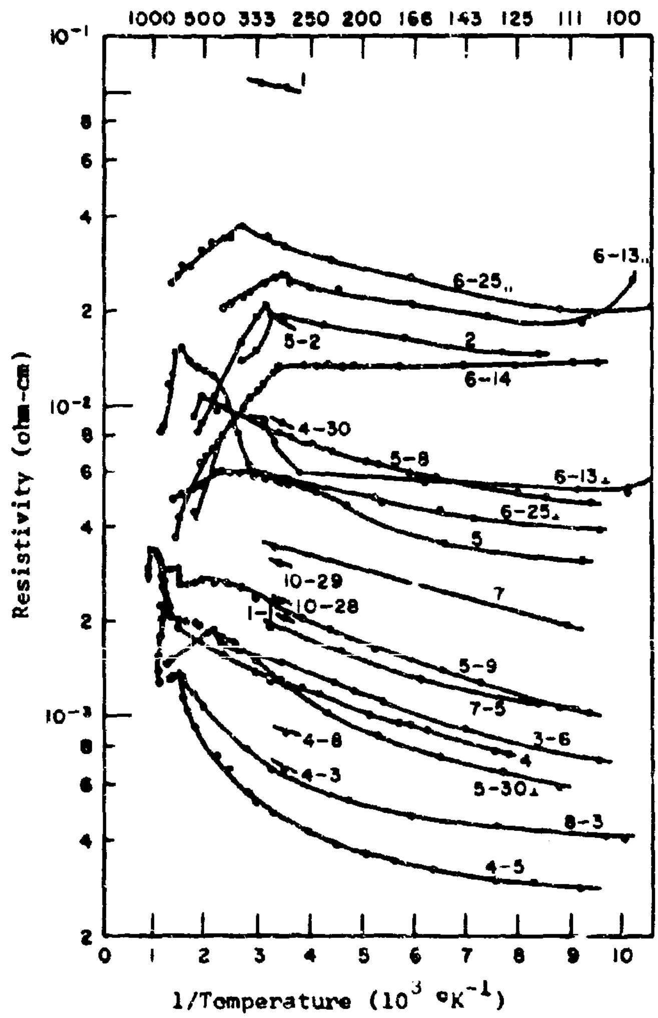
Electrical resistivity as a function of reciprocal temperature for single crystal, n-type Bi_2Se_3, parallel (0001). Temperature in °C is also given.

[Ref. 7839]

BISMUTH SELENIDE

ELECTRICAL RESISTIVITY

Sample	n, cm^{-3}	remarks
1	0.08	
1-1	0.25	
2	1.0	
3-6	2.1	zone melt
4	22.0	
4-3	52	
4-5	16	
4-8	1200	
4-30		
5	2.44	
5-2		
5-8	9.0	
5-9	3.0	
5-30	3.20	single crystal
6		single crystal
6-13	3.3	parallel
	2.5	normal
6-14	0.598	
6-14-1	0.74	
6-25	2.30	parallel, single crystal
	1.82	normal
7	1.5	0.077% In-doped
7-5	6.6	1.2% In-doped
8-3	6.28	
10-28		0.01% Cu-doped
10-29		0.1% Cu-doped



Electrical resistivity as a function of reciprocal temperature in single and polycrystalline Bi_2Se_3.

[Ref. 3097]

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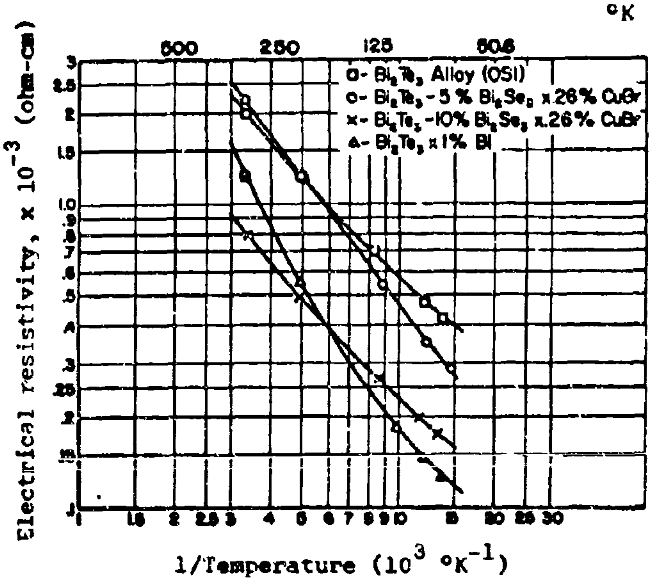
BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

ELECTRICAL RESISTIVITY

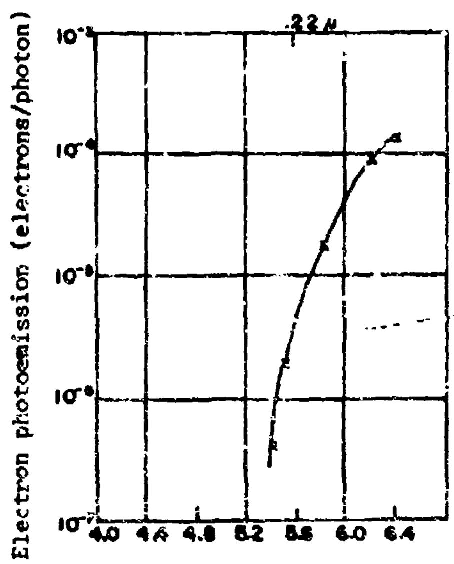


Electrical resistivity as a function of temperature for two Bi_2Te_3-Bi_2Se_3 alloys, also two Bi_2Te_3 samples, one is n-type, the other is p-type.

[Ref. 15503]

BISMUTH TELLURIDE

ELECTRON PHOTOEMISSION



Electron photoemission yield as a function of photon energy for freshly cleaved single crystal Bi_2Te_3, (0001), at 300°K and fields up to ∿ 5 volts.

[Ref. 493]

BISMUTH TELLURIDE

ELECTRONIC SPECIFIC HEAT (γ)

Symbol	Value	Sample	Test Method	Temperature	Ref.
γ	$17 \pm 8 \times 10^{-5}$ joul/deg^2/g-atom	macrocrystalline p-type	specific heat	1.37-65°K	7764

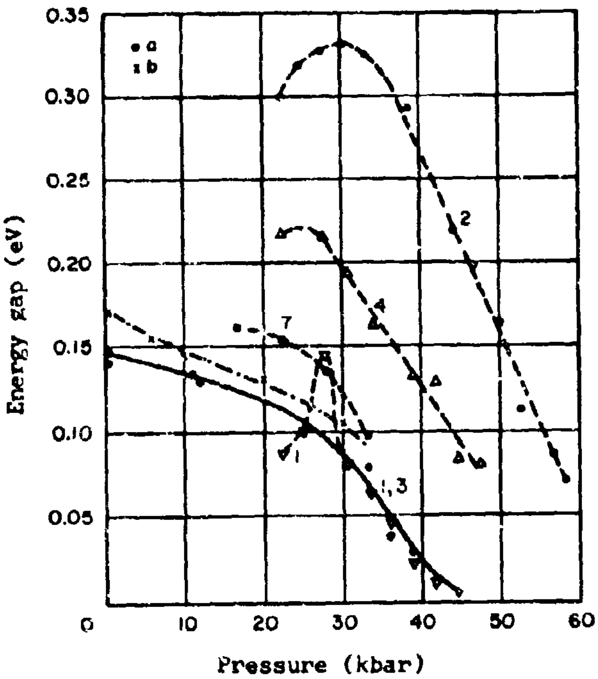
BISMUTH TELLURIDE, BISMUTH SELENIDE, and the BISMUTH TELLURIDE-BISMUTH SELENIDE SYSTEM

ENERGY BANDS

Symbol	Value	Sample (single crystal)	Measurement Method	Temperature	Ref.
		Bi_2Te_3			
$\Delta Eg/\Delta T$	-0.95×10^{-4} eV/°K	p-type, cleavage parallel to (0001), nearly intrinsic	optical absorption	118, 152 & 293°K	3124
$\Delta Eg/\Delta T$	-0.9×10^{-4} eV/°K	p-type, $n_{300K} = 10^{19}$/cc	IR transmission	77 & 300°K	2866
$\Delta Eg/\Delta P$	$\sim -2\times10^{-6}$ eV/atm	n-type, $n \sim 10^{17}$/cc .18 mm section	resistivity meas. 1 to 30 000 atm	200-400°K	21112
$\Delta Eg/\Delta P$	-6×10^{-6} eV/atm (above 25 000 atm)	p-type, (0001) oriented 0.1-0.3mm thick section	electrical resistivity	300°K	16204
$\Delta Eg/\Delta P \rightarrow 0$ above 40-45 kbar. $Eg \rightarrow 0$ (metallic state)					16204
		Bi_2Se_3			
$\Delta Eg/\Delta T$	-2×10^{-4} eV/°K	n-type, $n_{300K} = 2\times10^{19}$/cc	IR transmission	77 & 300°K	2866
$\Delta Eg/\Delta T$	$-5.$ to $-1.\times10^{-4}$ eV/°K	n-type	reflectivity	77-300°K	22468
		60% Bi_2Se_3-40% Bi_2Te_3			
$\Delta Eg/\Delta T$	-5×10^{-4} eV/°K	n-type	reflectivity	77-300°K	22468

BISMUTH TELLURIDE

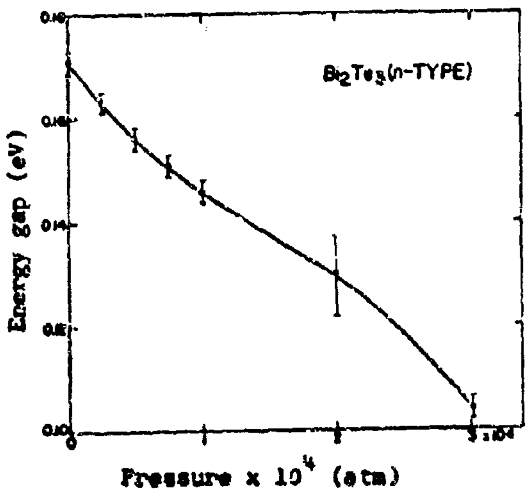
ENERGY BANDS



Effect of pressure on energy gap for p-type, single crystal Bi_2Te_3, (0001). a) Measured by the hydrostatic method; b) data from [Ref. 21112]. Although the slope remains fairly constant the absolute values vary, due possibly, to deformation during experiment.

Sample 1 and 2 are cut from one single crystal, 3, 4, and 7 from another single crystal.

[Ref. 16204]



Shift in energy gap with pressure in n-type, single crystal Bi_2Te_3, n ~ 10^{17}/cc. At 1 atm. measurements were made from 199-393°K. At higher pressures, 300°K was the lower temperature limit.

[Ref. 21112]

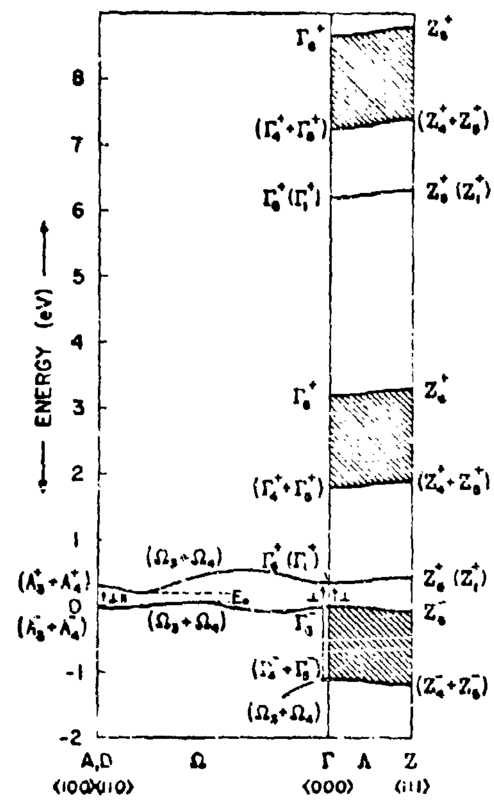
BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

ENERGY BANDS

ΓA and ΓD are degenerate. Five bands nearly horizontal across the ΓZ direction are assumed. They show small energy differences at Γ and Z. $\Gamma_6(\Gamma_1)$ characterizes the Γ_6 states arising from nondegenerate states of the single group.

The scheme explains the occurrence of the satellite peaks in the reflectivity spectra of the alloys as the energy distance of a certain gap at Γ and Z increases and resolution in the spectra becomes possible.

Derived from reflectivity data at 77-300°K on single crystal Bi_2Te_3, Bi_2Se_3 and polycrystalline alloys of these two compounds in varying proportions.



[Ref. 22468]

"In Bi_2Te_3 the surfaces of constant energy are almost spheroidal and are highly compressed in a direction nearly parallel to the three-fold axis of rotation of the crystal."

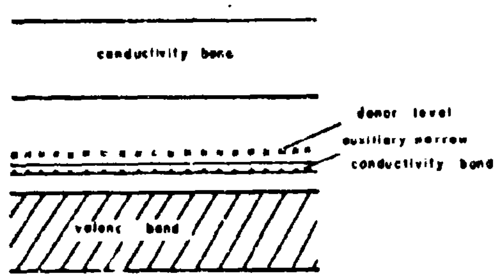
[Ref. 2360]

"In Bi_2Se_3 the surfaces of constant energy are ellipsoidal and are compressed in the x-direction and extended nearly parallel to the three-fold axis of rotation."

[Ref. 3350]

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

ENERGY BANDS



If a few donors are present over the narrow conductivity band, then weak n-type conductivity occurs at low temperatures. As the temperature rises, transitions take place from the valence to the narrow conduction band. As the narrow band is filled, the conductivity increases. As a consequence of the temperature dependence of the mobility, there is a conductivity decrease until intrinsic conductivity begins, i.e., until there is a transition of electrons into the main conductivity band. Because of the higher mobility in this band, there ensues the second sign change in the Hall field and the thermal emf. Since the energy gap is smaller for the telluride than the mixed telluride-selenide, the narrow band for the bismuth telluride possibly lies nearer the conductivity band, with the result that the saturation effect in the electrical conductivity is covered by the intrinsic conductivity.

[Ref. 10984]

BISMUTH TELLURIDE

ENERGY GAP (Eg)

Value(eV)	Sample	Test Measurement	Temperature	Ref.
0.16	single and macrocrystalline, intrinsic (iodine compensated)	electrical conductivity	0°K	2595
0.171	single crystal, n-type, n ∿ 10^{17}/cc	electrical resistivity, 1-30 000 atm., 199-393°K	0°K	21112
0.21	single crystal, p-type, cleavage normal to c-axis (0001) n_p = 1.4×10^{19}/cc	electrical	0°K	407
0.16*	single crystal, highly purified	optical	77°K	2866
0.18	single crystal, less pure	"	"	2866
0.20	single crystal, cleavage plane (0001) n-type, n = 3 and 9×10^{17}/cc, p-type, n = 3 and 4×10^{18} zone refined, p-type, n = 2×19^{19}	electrical	77-375°K	801
0.13	single crystal, p-type, intrinsic, parallel (0001)	optical, λ = 8-14μ	300°K	3124
0.14	single crystal, p-type, (0001) n = 5×10^{17}/cc	electrical conductivity	300°K	10535
0.15*	single crystal, highly purified	optical	300°K	2866

* value for purest material

BISMUTH SELENIDE

ENERGY GAP (Eg)

Value (eV)	Sample	Test Measurement	Temperature	Ref.
0.275	polycrystalline	IR transmission	300°K	2785
0.35	single crystal	IR optical and transition	300°K	2866
0.40	"	"	77°K	2866
0.36	single crystal, n-type, parallel (0001), $n_{300K} = 5 \times 10^{17}$/cc	electrical	> 750°K	7839
0.23	polycrystalline, n-type	elec. resist.	0°K	3097
0.2	"	optical abn. at 1-8μ		
0.4	"	elec. resist.		3097

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

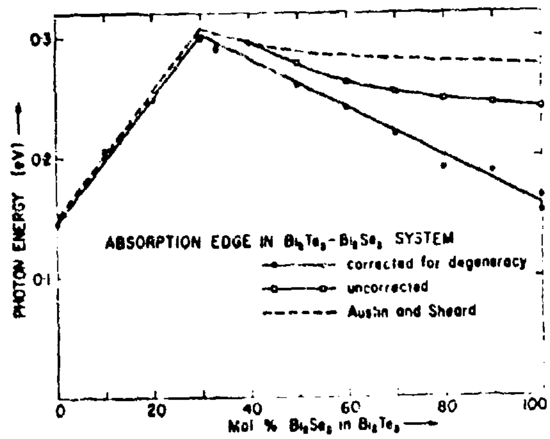
ENERGY GAP (Eg)

Thermal (eV)	Optical (eV)	single crystal, doped or compensated, $0 \leq x \leq 1$, (low conductivity)			
0.16	0.15	Bi_2Te_3	electrical	300°K	10984
0.22	0.20	$Bi_2Te_{2.7}Se_{0.3}$			
0.29	0.30	Bi_2Te_2Se			10984

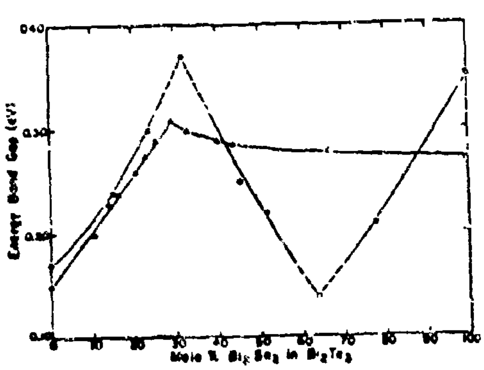
BISMUTH TELLURIDE-BISMUTH SELENIDE SYSTEM

ENERGY GAP

Absorption edge as a function of composition in single crystal samples in the bismuth telluride-bismuth selenide system. Incident illumination normal to (0001) cleavage plane.



[Ref. 22468]



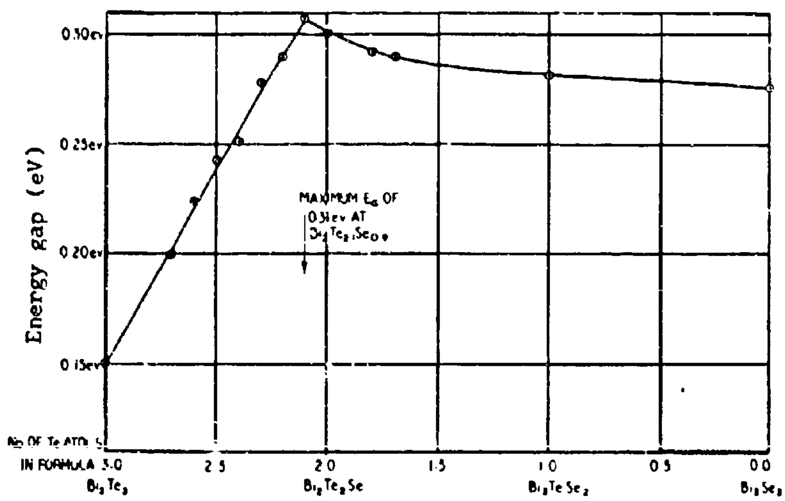
Energy gap as a function of composition for single crystal sample. Data taken by electrical resistivity measurements, parallel to (0001).

- ● Miller et al. (thermal) [Ref. 15551]
- ◻ Smith et al. (thermal) [Ref. 7839]
- ◻ Black et al. (optical) [Ref. 2866]
- ▲ Austin and Sheard (optical) [Ref. 2785]

[Ref. 15551]

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

ENERGY GAP



Energy gap as a function of composition for Bi_2Te_3-Bi_2Se_3. Samples were polycrystalline and purified. A single hexagonal phase was shown with slight point-to-point inhomogeneity in samples with over 16 at.% of selenium.

[Ref. 2785]

BISMUTH TELLURIDE

ENERGY LEVELS

Symbol	Value (eV)	Dopant	Sample	Test Method	Temperature	Ref.
E_m	0.5[illegible]-0.7	deformation for Bi vacancies and	single crystal, p-type	elec. resist.	300°K	5890
E_m	1.09-1.1	Te vacancies	"	"	"	5890

E_m is an activation energy for vacancy motion arising from plastic deformation which introduces defects that change p-type material to n-type.

Oxygen and copper act as donors.

E_A	∿ 0.4	Ge	macrocrystalline, normal (0001), $n = 2x10^{19}/cc$	electrical conductivity	300°K	15813

Stoichiometric Bi_2Te_3 is always p-type, but excess Te or halogens change it to n-type. The very high diffusion rate of copper in Bi_2Te_3 produces an n-type material. 2595

Iodine acts as a donor in Bi_2Te_3. Tin apparently is associated with a trapping level at 0.01 eV as is seen from Hall measurements between 77° and 200°K. 8730

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BISMUTH SELENIDE

ENERGY LEVELS

Symbol	Value (eV)	Sample	Test Method	Temperature	Ref.
E_D	0.09_{CB}	single crystal, n-type, parallel (0001), $n_{300K} = 5x10^{17}/cc$	resistivity and Hall	125-350°K	7839

0.01% Bi_2O_3 added to $Bi_2Te_{2.4}Se_{0.6}$ polycrystalline, n-type, n ∿ 10^{19}/cc, causes a 40% decrease in conductivity, but no change in thermal emf. Further addition has no effect on conduction. 4382

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BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

ENERGY LEVELS

Composition mol % Bi_2Te_3	Bi_2Se_3	Thickness (μ)	α (μV/deg)	Type	ζ^*	$\zeta - E_{co}$ at 300°K (eV)	λg (μ)	E_g (eV)	$E_{g\,corr}$ (eV)
100	—	3	253	p					
100	—	17	253	p	−1.2		8.53	0.145	0.145
90	10	20	217	p	−0.7		5.98	0.203	0.203
90	10	31	217	p	−0.7		6.10	0.207	0.207
80	20	8	229	p	−0.9		4.95	0.246	0.246
80	20	30	224	p	−0.85		5.05	0.250	0.250
70	30	40	−246	n	−0.9		4.15	0.299	0.299
66.7	33.3	21	−240	n	−0.75		4.30	0.287	0.259
60	40	38	−218	n	−0.5		4.20	0.295	0.295
50	50	29	−153	n	0.7	0.018	4.45	0.278	0.260
40	60	39	−148	n	0.75	0.02	4.73	0.262	0.242
30	70	21	−120	n	1.3	0.054	4.90	0.253	0.219
20	80	15	−90	n	2.2	0.057	5.00	0.248	0.191
10	90	31	−91	n	2.2	0.057	5.08	0.244	0.187
0	100	25	−66	n	3.3	0.066	5.15	0.241	0.155
0	100	18	−55.5	n	~4.0		5.38	0.230	
0	100	25	−73	n	3.0	0.078	5.06	0.245	0.167

The Fermi level and energy gap values in this table, are derived from reflectivity data for a series of single crystal members of the bismuth telluride-bismuth selenide system. Measurements are made at 0.1 to 12 eV and 300°K. Incident light is both normal and parallel to the (0001) cleavage plane.

α is the thermoelectric emf

ζ^* is the reduced Fermi level and is determined from thermoelectric data

Eg is the energy gap determined at the wavelength corresponding to an interband contribution of $K_{int} = 600\ cm^{-1}$

λg is the incident wavelength in microns

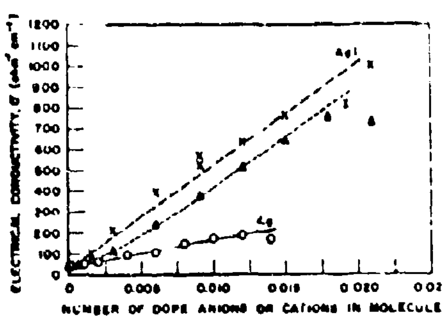
The energy gap values are also corrected for degeneracy.

[Ref. 22468]

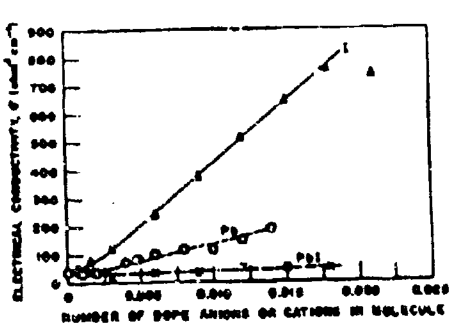
BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

ENERGY LEVELS

Electrical conductivity as a function of dopant concentration in polycrystalline $Bi_2Te_{2.1}Se_{0.9}$. The dopant is added as either silver, iodine or the silver iodide; the increase in conductivity is cumulative. In the case of the lead, lead iodide or iodine additions, the iodine produces n-type material, whereas the lead yields p-type, resulting in a compensating action for the lead iodide.



[Ref. 316]



Electrical conductivity as a function of dopant concentration in polycrystalline $Bi_2Te_{2.1}Se_{0.9}$.

[Ref. 316]

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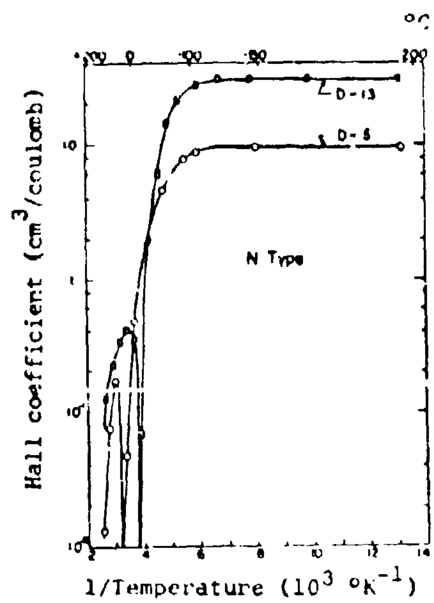
BISMUTH TELLURIDE

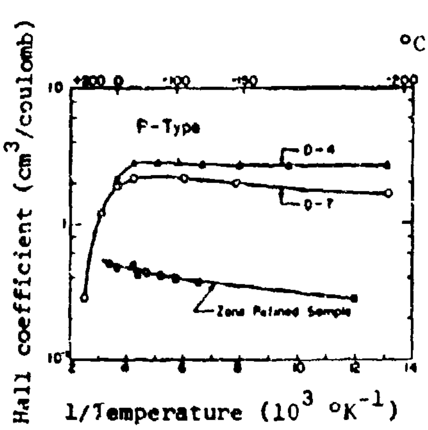
HALL COEFFICIENT (R_H)

Hall coefficient as a function of reciprocal temperature in single crystal, n-type bismuth telluride. The current and Hall voltage were parallel to the cleavage plane, and the magnetic field was perpendicular to the cleavage plane.

Sample	n, cm^{-3}
D-13	$3x10^{17}$
D-5	$9x10^{17}$



[Ref. 801]



Hall coefficient as a function of reciprocal temperature in single crystal, p-type bismuth telluride. The current and Hall voltage were parallel to the cleavage plane and the magnetic field was perpendicular to the cleavage plane.

Sample	n, cm^{-3}
D-4	$3x10^{18}$
D-7	$4x10^{18}$
Zone refined sample	$2x10^{19}$

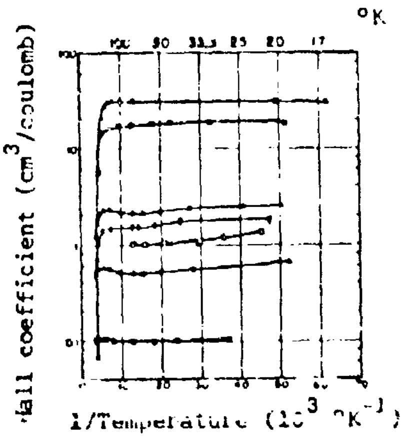
[Ref. 801]

BISMUTH TELLURIDE

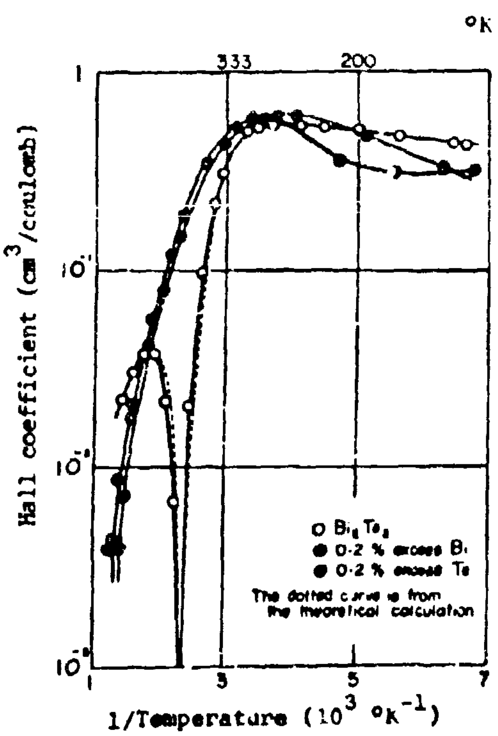
HALL COEFFICIENT

Hall coefficient as a function of reciprocal temperature for single crystal, n-type Bi_2Te_3, Te-doped.

Symbol	n, cm^{-3}
△	2.4×10^{17}
□	5.3×10^{17}
▲	3.0×10^{18}
◇	3.4×10^{18}
●	1.2×10^{19}
■	6.8×10^{19}
○	no data given



[Ref. 14854]



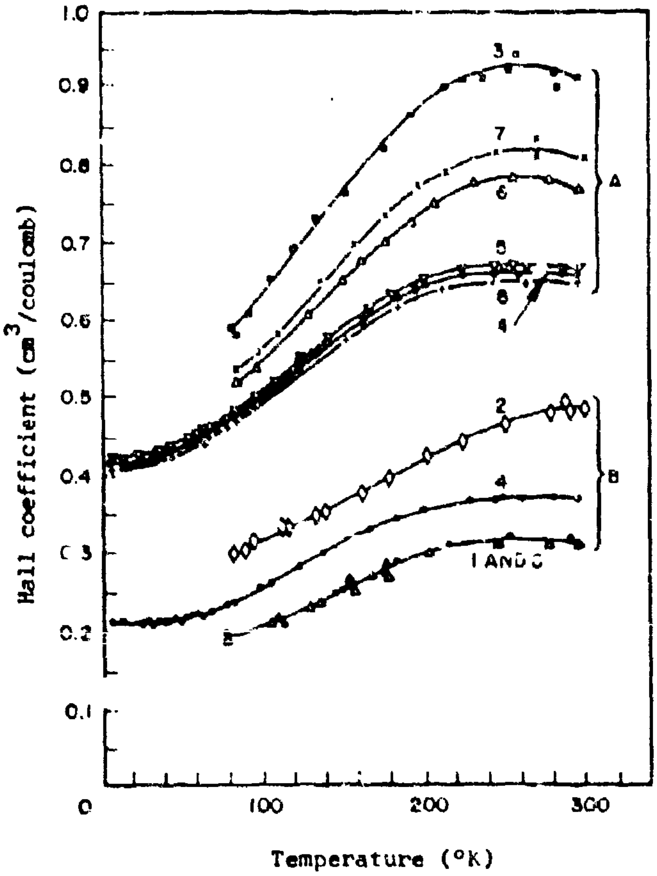
Hall coefficient in stoichiometric and 0.2% excess samples as a function of reciprocal temperature for p-type, single crystals, cut parallel to (0001) cleavage plane. Measurements were made at 4 kG, n = 1.4×10^{19}/cc.

[Ref. 407]

BISMUTH TELLURIDE

HALL COEFFICIENT

Sample			n, cm^{-3} at 290°K
○	1		-
◇	2		-
□	3		-
●	4	normal	8.2×10^{18}
▼	5	parallel	8.2×10^{18}
Δ	6		-
×	7		2.9×10^{18}
+	8		-



The Hall coefficient as a function of temperature for zone purified, p-type, single crystal Bi_2Te_3. A) indicates the ρ_{231} tensor component: B) indicates the ρ_{123} tensor component, except 4 which is the transverse component. All samples cut parallel to the (0001) cleavage plane.

[Ref. 2984]

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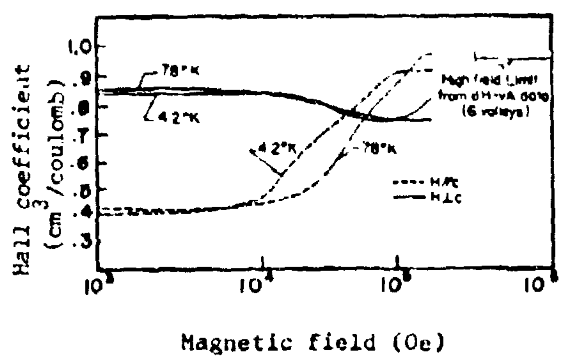
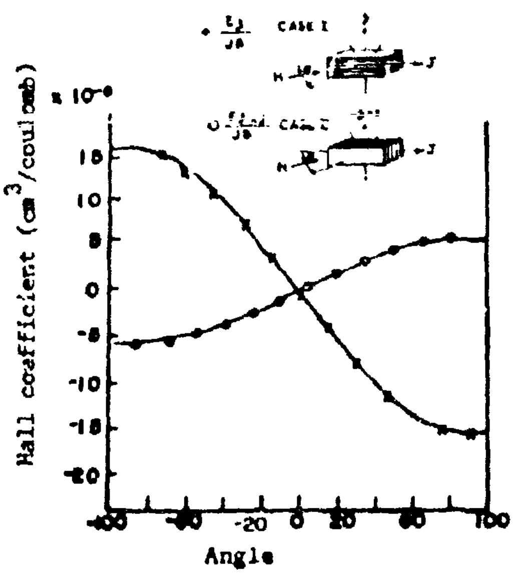
BISMUTH TELLURIDE

HALL COEFFICIENT

Hall coefficient as a function of field for single crystal, p-type Bi_2Te_3 at 160 kG and 2 temperatures. Field is parallel or normal to (0001) cleavage plane.



[Ref. 11903]



Hall coefficient as a function of angle between field and current at 77°K, in single crystal, n-type Bi_2Te_3 with high iodine doping, cut parallel to (0001) cleavage plane.

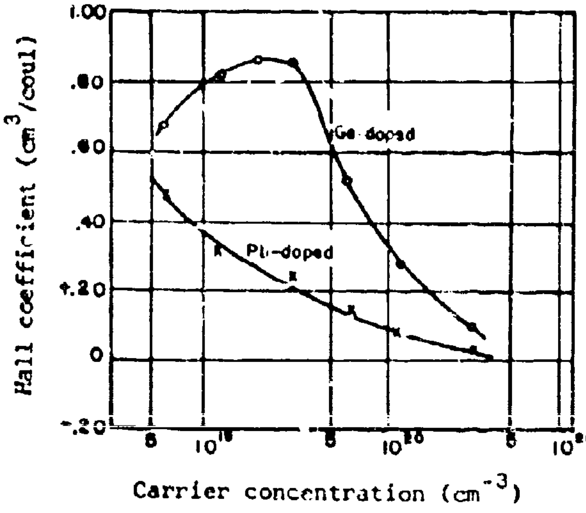
+ data for field normal to (0001)

o data for field parallel to (0001).

[Ref. 19045]

BISMUTH TELLURIDE

HALL COEFFICIENT

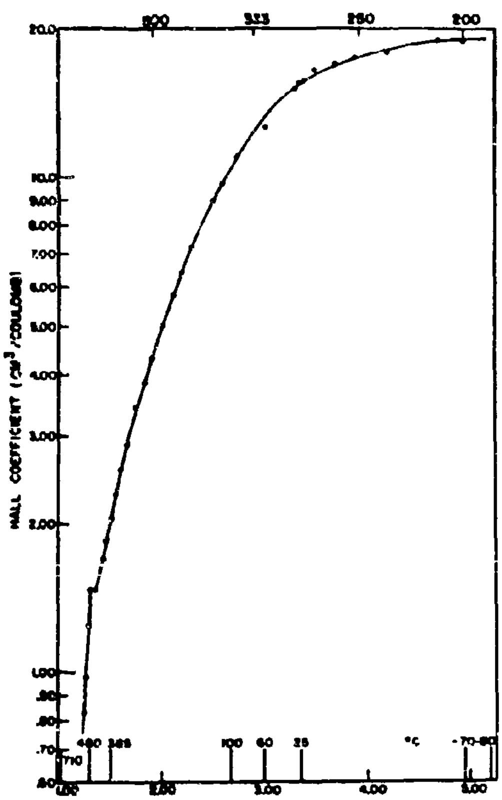


Hall coefficient as a function of carrier concentration at 300°K for macrocrystalline Bi_2Te_3. Lead-doped samples show steady decrease, whereas Ge-doped material has a maximum at $2x10^{19}$/cc.

[Ref. 15813]

BISMUTH SELENIDE

HALL COEFFICIENT

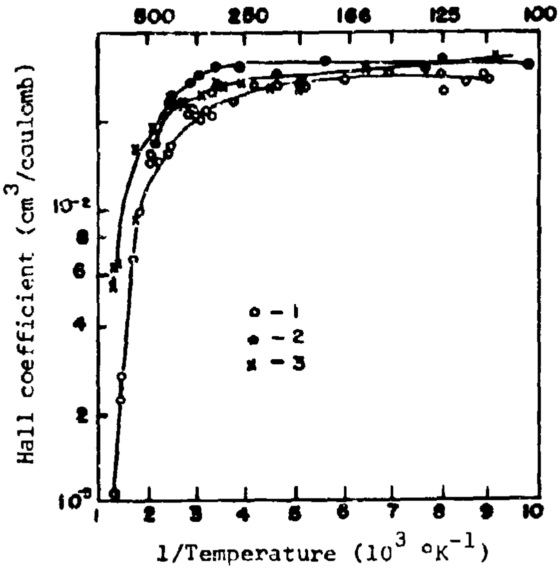


Hall coefficient as a function of reciprocal temperature for Bi_2Se_3 n-type, single crystal, parallel to cleavage plane, (0001).

[Ref. 7839]

BISMUTH SELENIDE

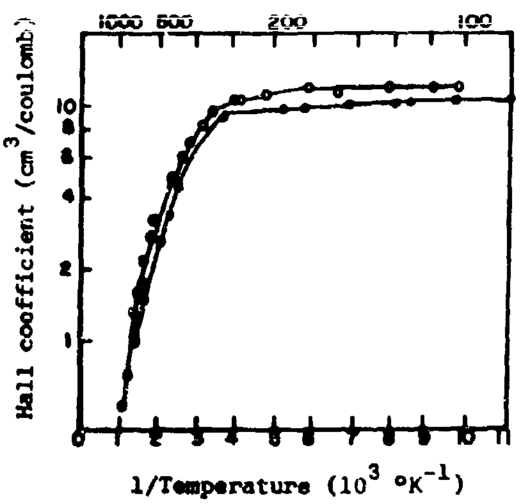
HALL COEFFICIENT



Hall coefficient as a function of reciprocal temperature for single crystal BiSe.

Sample	n, cm^{-3}
1	$2x10^{20}$
2	$2.5x10^{20}$
3	$2.2x10^{20}$

[Ref. 3097]



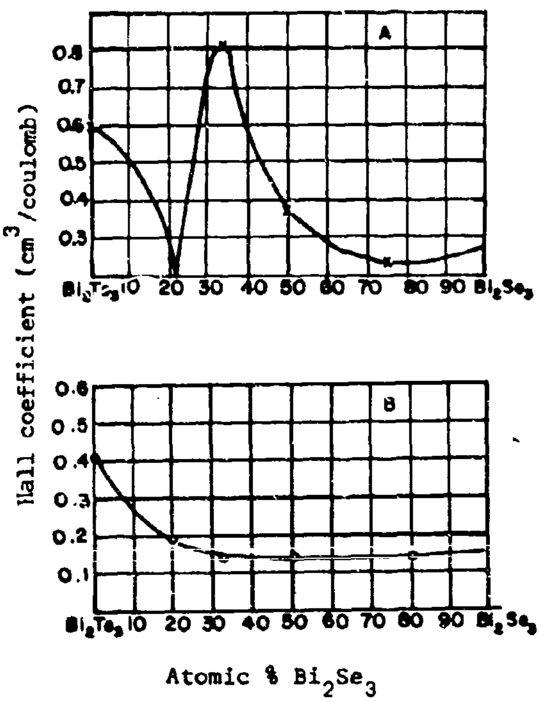
Hall coefficient as a function of reciprocal temperature in single crystal, n-type Bi_2Se_3.

Sample	n, cm^{-3}
o	$6x10^{17}$
•	$7x10^{17}$

[Ref. 3097]

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

HALL COEFFICIENT



Hall coefficient as a function of composition at 300°K, in single crystal Bi_2Te_3-Bi_2Se_3 mixed crystals. A) is undoped, B) is silver iodide doped.

[Ref. 3867]

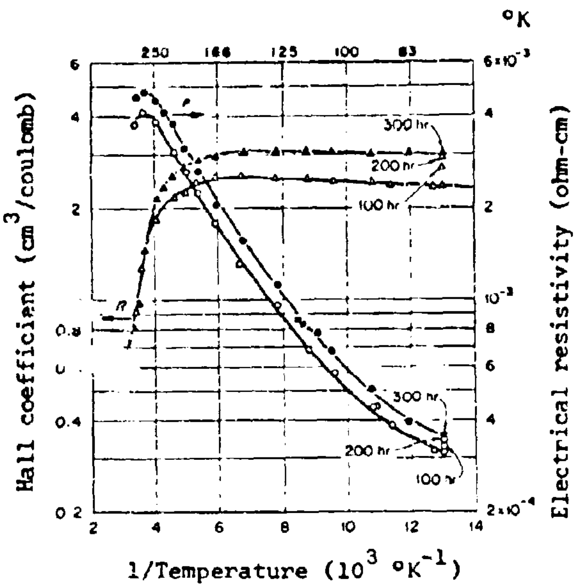
BISMUTH TELLURIDE

IRRADIATION PROPERTIES

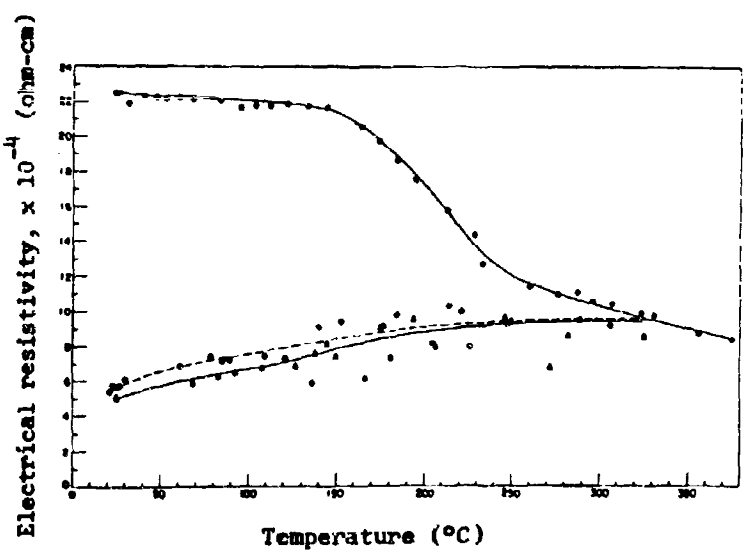
Hall coefficient and electrical resistivity before and after 300-hr Co^{60}-gamma radiation as a function of reciprocal temperature for single crystal, n-type Bi_2Te_3, n ∿ 10^{18}/cc. In n-type samples the mobility reaches 8500 cm^2/V sec at 77°K after prolonged irradiation; in p-type, the mobility reaches 7500.

Δ, o before irradiation and up to 200 hours irradiation

▲, ● after 300 hours irradiation.



[Ref. 16462]



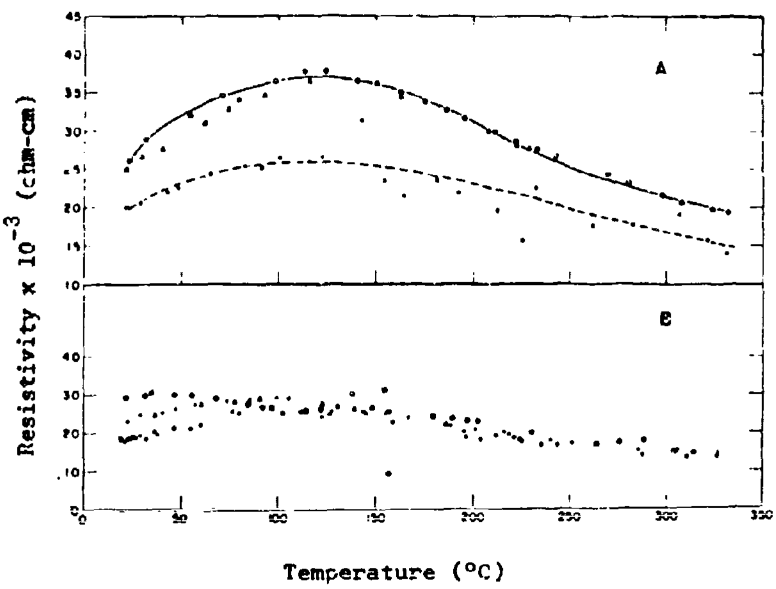
Electrical resistivity as a function of temperature in n-type polycrystalline Bi_2Te_3, irradiated by both thermal and fast neutrons to an integrated thermal flux of 1.5×10^{20} neutrons/cm^2 and $1.6\times10^{19}/cm^2$ flux of fast (> 1 meV) neutrons.

● Bi_2Te_3 irradiated without cadmium shield
▲ sample after annealing
o unirradiated sample

[Ref. 2737]

BISMUTH TELLURIDE

IRRADIATION PROPERTIES



Electrical resistivity as a function of temperature for p-type polycrystalline bismuth telluride, irradiated at about 33°K by both thermal and fast (> 1 meV) neutrons. Total flux 1.5×10^{20} thermal neutrons/cm^2 and 1.6×10^{19} fast (> 1 meV) neutrons/cm^2.

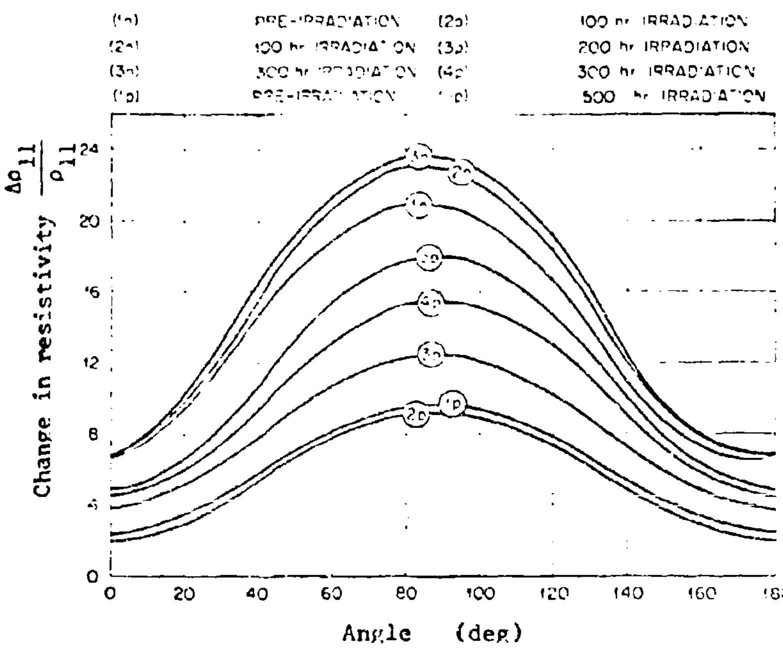
A
- ● unirradiated
- o run 1, cadmium shielded
- Δ run 2, cadmium shielded

B
- ● p-type, unirradiated
- o p-type, irradiated without cadmium shield
- +, Δ p-type, irradiated after annealing

[Ref. 2737]

BISMUTH TELLURIDE

IRRADIATION PROPERTIES

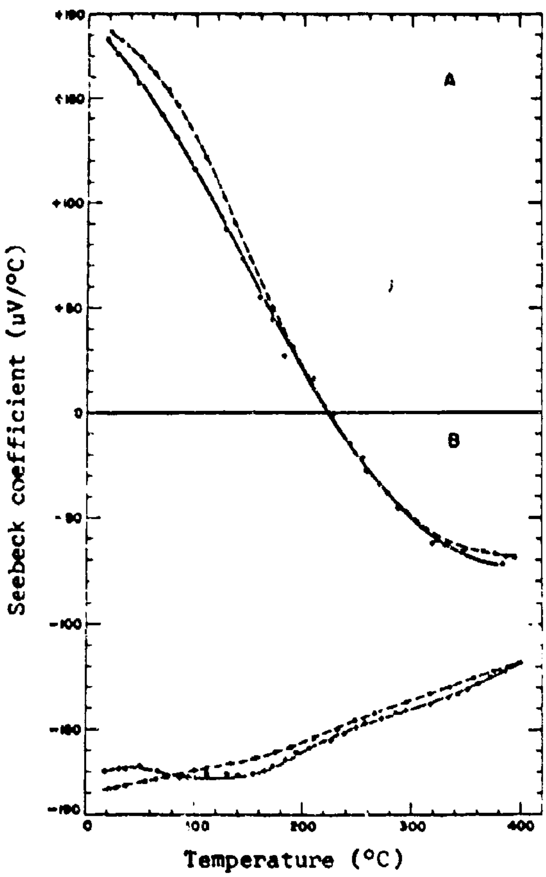


Magnetoresistance as a function of angle between current and magnetic field for single crystal, n-, and p-type Bi_2Te_3. Irradiation was with Co^{60}-gamma rays. Initial carrier concentration was 10^{18} to $10^{19}/cm^3$

[Ref. 16462]

BISMUTH TELLURIDE

IRRADIATION PROPERTIES



Comparison of Seebeck coefficients as a function of temperature in p-, and n-type, polycrystalline bismuth telluride samples unirradiated and irradiated without the cadmium shield, but subsequently annealed by slow step-wise heating to ∿ 400°C.

(A) • p-type unirradiated sample
+ p-type irradiated unshielded sample after annealing

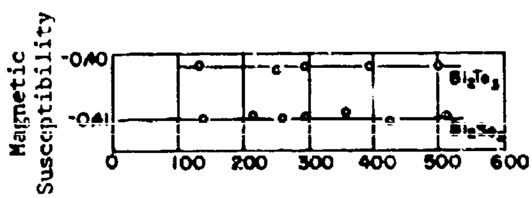
(B) • n-type sample unirradiated
+ n-type irradiated unshielded sample after annealing

[Ref. 2737]

BISMUTH TELLURIDE and BISMUTH SELENIDE

MAGNETIC SUSCEPTIBILITY (χ)

Symbol	Value (cm^3/g)	Material	Sample	Temperature	Ref.
χ	-0.402×10^{-6}	Bi_2Te_3	polycrystalline, p-type	130-500°K	5184
	-0.410×10^{-6}	"	"	"	5184

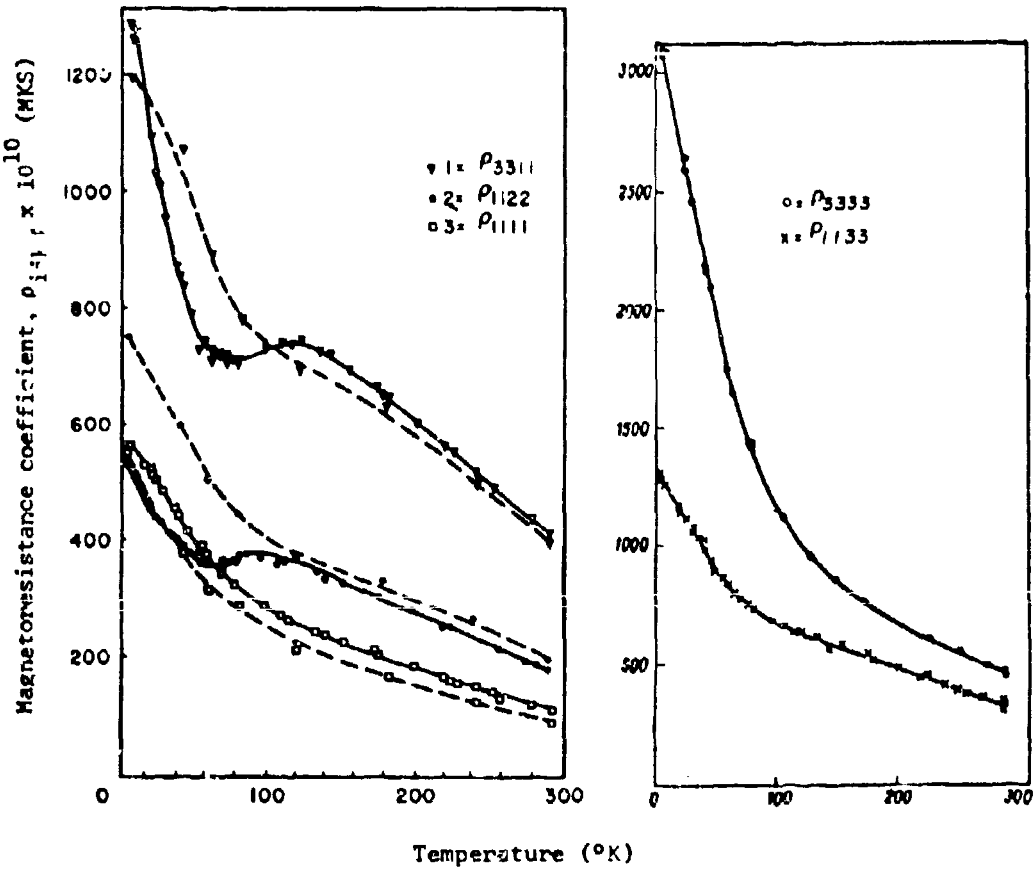


Magnetic susceptibility as a function of temperature for polycrystalline, n-type Bi_2Se_3 and p-type Bi_2Te_3.

[Ref. 5184]

BISMUTH TELLURIDE

MAGNETOELECTRIC PROPERTIES ($\Delta\rho/\rho_o$)



The five strong magnetoresistance coefficients are shown as a function of temperature for single crystal, p-type Bi_2Te_3, parallel to (0001) cleavage plane.

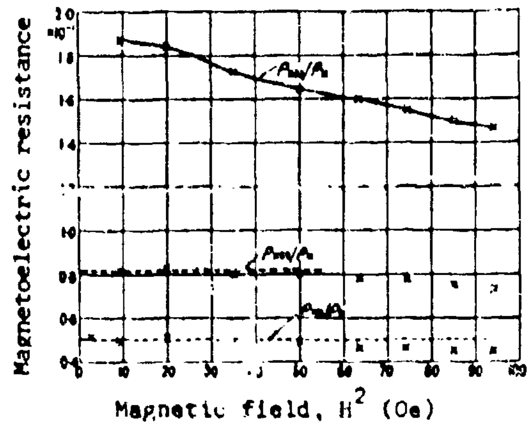
$$n = 8 \times 10^{18}/cc$$

[Ref. 2984]

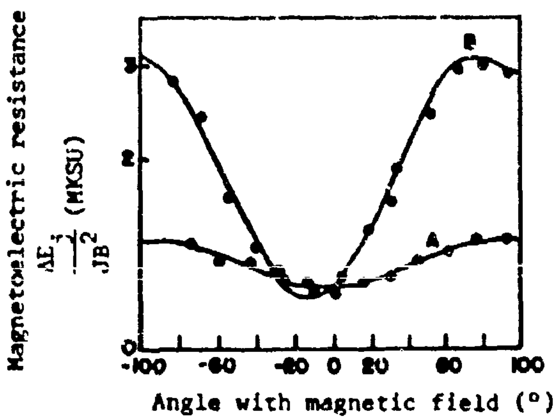
BISMUTH TELLURIDE

MAGNETOELECTRIC PROPERTIES

Magnetoelectric resistance coefficients as a function of magnetic field at 77°K for single crystal, n-type Bi_2Te_3, in (0001) cleavage plane.



[Ref. 2360]



Magnetoelectric resistance as a function of angle at 77°K for single crystal, n-type, highly I-doped Bi_2Te_3.

(A) ● field normal to (0001)
(B) ○ field is parallel to (0001)

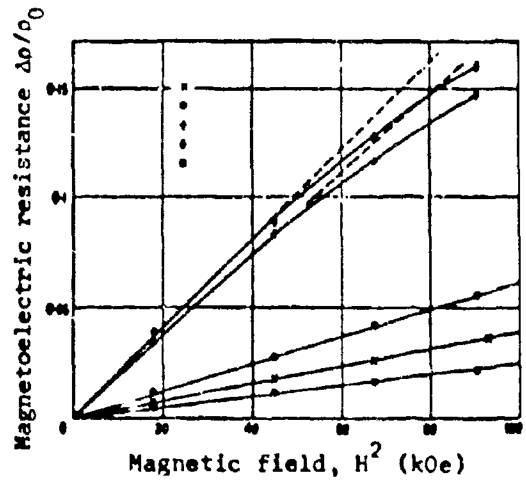
[Ref. 19045]

Magnetoelectric resistance as a function of field at 77°K for single crystal, n-, and p-type Bi_2Te_3, cut parallel to (0001) cleavage plane. Slightly iodine-doped samples deviate from linearity.

× ● } p-type, undoped

+ ♦ ■ } n-type, iodine-doped

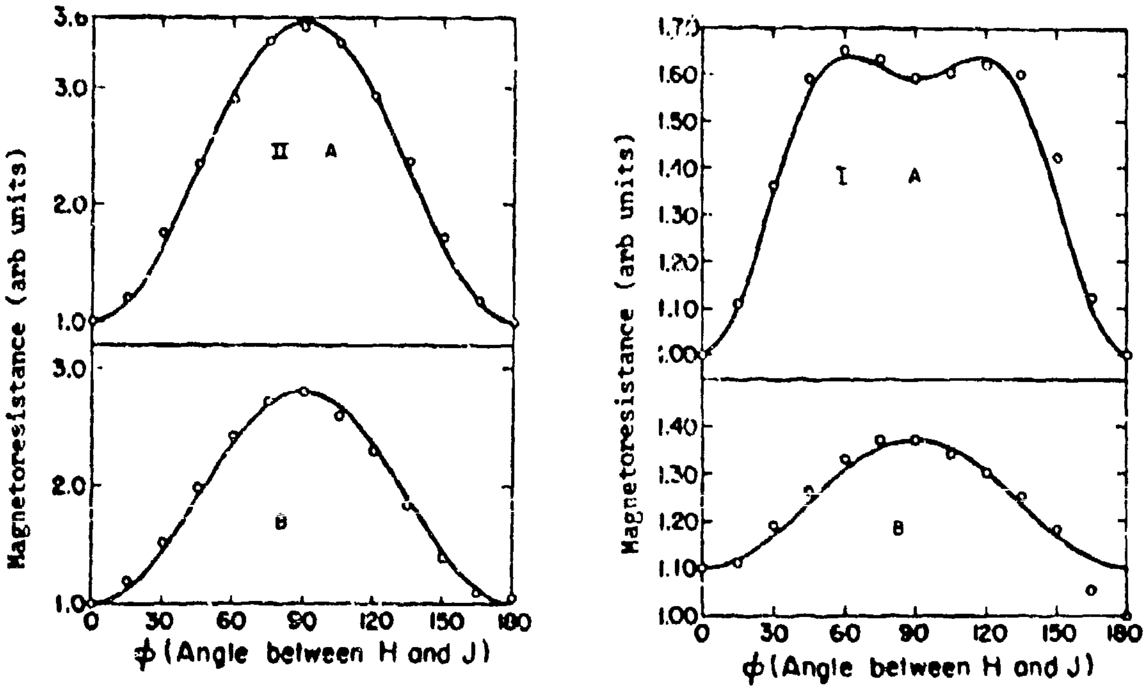
↓ increasing I content



[Ref. 3215]

BISMUTH TELLURIDE

MAGNETOELECTRIC PROPERTIES



Magnetoresistance as a function of angle between current and field at 77°K. The two samples (A and B) of Bi_2Te_3 are single crystal, n-type, cut on (0001) cleavage plane, $n = 3 \times 10^{18}$/cc.

For sample A, field is 6000 G; for sample B, it is 975 G.

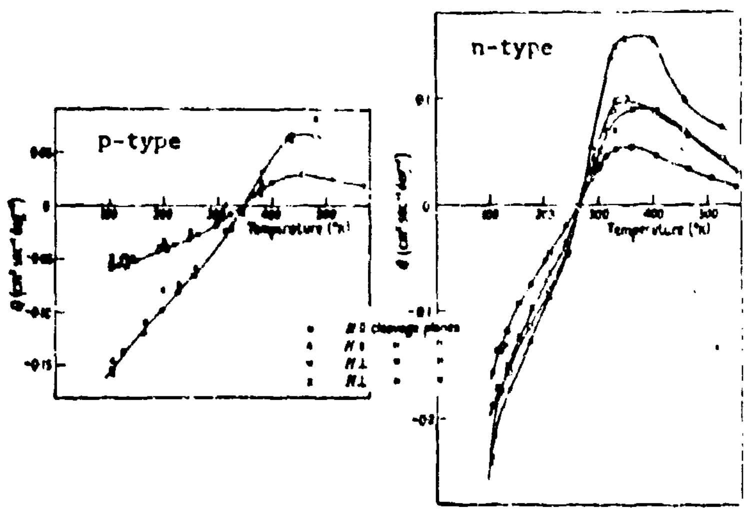
I Field is parallel (0001)

II Field is normal (0001)

[Ref. 17748]

BISMUTH TELLURIDE

MAGNETOELECTRIC PROPERTIES

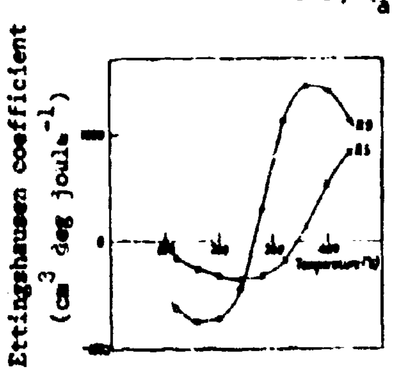


Nernst coefficient as a function of temperature for single crystal, n-, and p-type Bi_2Te_3 for fields parallel and normal to cleavage plane, (0001).

▲ x, Q_i is the isothermal coefficient

● o, Q_a is the quasi-adiabatic coefficient

[Ref. 3360]



Ettingshausen coefficient as a function of temperature in single crystal, n- or p-type Bi_2Te_3. Magnetic field is normal to (0001) cleavage plane.

R_5 is p-type

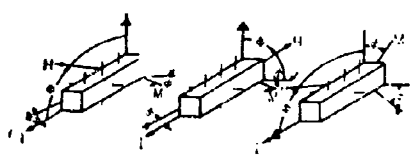
R_9 is n-type

[Ref. 3360]

BISMUTH SELENIDE

MAGNETOELECTRIC PROPERTIES

Sample	A	B		Units
Temp. (°K)	4.2	90		
	Obs.	Obs.	Calc.	
σ_{11} σ_{33}	+ 3.5 + 0.59	2.10 0.45	$\times 10^{3}$ $(ohm^{-1})(cm)^{-1}$	σ in $(ohm\text{-}cm)^{-1}$
σ_{312} σ_{123}	− 0.40_1 − 2.50	0.26 1.28	$\times 10^{4}$ $(ohm)^{-2}(cm)(coul)^{-1}$	$R_H\ \sigma^2$ $(cm/ohm^2\ coul)$
σ_{1111} σ_{1122} σ_{1133} σ_{1123} σ_{3311} σ_{3333} σ_{2311} σ_{2323}	− 0.7 − 4.8 −24.4 − 0.1 − 0.8_1 − 1.4_2 − 0.53 + 1.6	0.12 1.7 10 0.20 0.47 0.6 0.12 1.7	$\times 10^{9}$ $(ohm)^{-3}(cm)^{3}(coul)^{-2}$	$R_H^{\ 2}\ \sigma^3$ $(cm^3/ohm^3\ coul^2)$
σ_{11}/σ_{33}	+ 5 °	4.7	5.36	
$\sigma_{123}/\sigma_{312}$	+ 5.2	4.9	5.36	
$\sigma_{1111}/\sigma_{1133}$ $\sigma_{1122}/\sigma_{1133}$ $\sigma_{1123}/_{1133}$ $\sigma_{3311}/\sigma_{1133}$ $\sigma_{3333}/\sigma_{1133}$ $\sigma_{2311}/_{1133}$ $\sigma_{2323}/\sigma_{1133}$	+ 0.029 + 0.20 + 0.004 + 0.003 + 0.058 + 0.022 − 0.065	0.012 0.17 0.020 0.047 0.06 0.012 0.17	0.045 0.202 0.0486 0.0344 0.0590 0.0091 0.0930	



Experimental arrangements. *H* the magnetic field, *I* the electric current, ▲ the three-fold axis, ● the two-fold axis, *M* the axis along the mirror plane and ϕ the rotatory angle of magnetic field.

Experimental and calculated magnetoelectric coefficients of single crystal, n-type Bi_2Se_3 at 4.2°K. Sample B data from [3350]. Calculated data is derived from an ellipsoidal six valley model for conduction band minima.

[Ref. 12046]

BISMUTH TELLURIDE

MOBILITY (μ)

Symbol	Value (cm^2/V sec)	Temp. coeff.	Sample (single crystal)	Temperature	Ref.
μ_n	4600		n-type, I-doped, $n = 2.07 \times 10^{19}$/cc $\rho_{77K} = 6.57 \times 10^{-5}$ ohm-cm	77°K	4487
μ_n	200-1000	$T^{-2.3}$	p-type, $n = 1.4 \times 10^{19}$/cc	300-140°K	407
μ_n	1250		n-type	286°K	2360
μ_n		$1.67 \times 10^7\ T^{-1.68}$		150-300°K	
μ_p	330			300°K	2360
μ_n	800		p-type, $n = 10^{19}$/cc, $\rho = 1.6 \times 10^{-3}$ ohm-cm	300°K	2866
μ_p	400		"	"	2866
μ_n	540		n-type, excess Te & I $n_n = 5 \times 10^{18}$/cc	300°K	2624
μ_p	400		p-type, excess Bi & Pb $n_p = 8 \times 10^{18}$/cc	300°K	2624

Symbol	Value (cm^2/V sec)	n, cm^{-3}	Sample (single crystal)	Temperature	Ref.
μ_n	310	3×10^{17}	n-type	300°K	801
μ_p	440				
μ_n	240	9×10^{17}			
μ_p	330				
μ_p	410	2×10^{19}	p-type		
μ_p	430	3×10^{18}			
μ_p	680	4×10^{18}			801

BISMUTH TELLURIDE

MOBILITY

Symbol	Value (cm^2/V sec)	Temp. coeff.	Sample	Temperature	Ref.
μ_n	400		single or polycrystalline, n-type, parallel (0001)	300°K	631
	10		normal (0001)	300°K	
μ_n		T^{-3}	parallel (0001)	273-560°K	631
μ_n	350		macrocrystalline, p-type (undoped)	300°K	3867
μ_p	265				
μ_p	350		AgI-doped, n = 2-18x10^{19}/cc		
μ_p	149-18*		Sn-doped, n = 3-33x10^{19}/cc		3867

* Hole mobility decreases with increase in Sn-doping

Symbol	Value (cm^2/V sec)	Temp. coeff.	Sample	Temperature	Ref.
μ_p	280		single crystal, p-type, ρ = .055 ohm-cm	300°K	10535
μ_p		$T^{-1.3\ to\ -1.6}$	n = 5x10^{17}/cc	4-250°K	10535
μ_p	515		single crystal, p-type	290°K	3207
μ_p		$T^{-1.98}$	" "	77-290°K	3207
μ_p		$1.2\times10^{8}\ T^{-2.3}$	single crystal, p-type n = 1.4x10^{19}/cc	140-300°K	407
			single or polycrystalline (0001)	150-300°K	2595
μ_n		$\sim T^{-1.72}$	n-type		
μ_p		$\sim T^{-1.94}$	p-type		2595

BISMUTH TELLURIDE

MOBILITY

Symbol	Value cm^2/V sec	Value Temp. coeff.	Sample	Temperature	Ref.
μ_n		$\sim T^{-1.78}$	polycrystalline, CuBr doping yields n-type, $n = 2\text{-}20\times10^{19}/cc$	80-600°K	14525
μ_p		$\sim T^{-2.12}$	Pb-doped yields p-type, $n = 2\text{-}10\times10^{19}/cc$	"	14525
μ	1.8×10^5 (max)		single crystal, Te-doped, $n = 9\times10^{17}/cc$	4.2°K	14854
μ_n		$T^{-2.8}$	$n = 2.4\times10^{17}$	4.2-250°K	
		$T^{-2.7}$	5.3×10^{17}		
		$T^{-2.2}$	3.0×10^{18}		
		$T^{-2.4}$	3.4×10^{18}		
		$T^{-1.70}$	1.2×10^{19}		
		$T^{-1.31}$	6.8×10^{19}		14854

μ_n is electron mobility

μ_p is hole mobility

BISMUTH SELENIDE

MOBILITY

Symbol	Value cm^2/V sec	Value Temp. coeff.	Sample	Temperature	Ref.
μ_n	700		macrocrystalline, n-type, $n \sim 10^{19}/cc$	300°K	2538
μ_n	600		single crystal, n-type, $\rho = 5x10^{-4}$ ohm-cm, $n = 2x10^{19}/cc$	300°K	2866
μ	300-500		single crystal, n-type, parallel (0001), $n = 2\text{-}4x10^{19}/cc$, $\rho = .001$ ohm-cm	300°K	630
μ	10-20		normal (0001), $n = 2\text{-}4x10^{19}/cc$ $\rho = .02$ ohm-cm	300°K	630
		$T^{-.5}$	parallel (0001)	130-300°K	630
		$T^{-1.5}$	"	300-500°K	
		T^{-3}	"	> 500°K	630
μ	442		macrocrystalline, n-type, AgI-doped	300°K	3867

BISMUTH TELLURIDE-BISMUTH SELENIDE

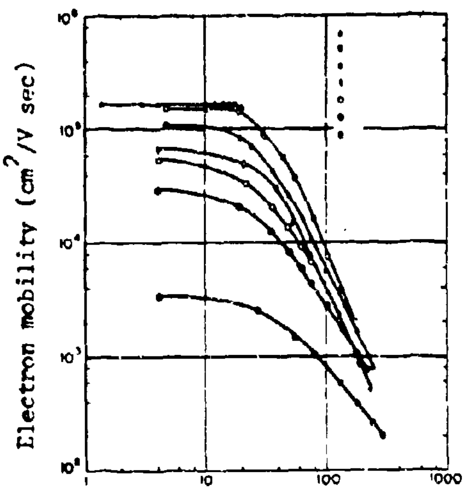
Symbol	Value cm^2/V sec	Value Temp. coeff.	Sample	Temperature	Ref.
μ	22.		75% Bi_2Te_3-25% Bi_2Se_3 AgI-doped film annealed, $n \cong 1.5x10^{19}/cc$ $\rho \sim 10^{-4}$ ohm-cm	300°K	21023
	0.5		film not annealed, $n = 2.9x10^{20}$ $\rho \sim .01$ to .3 ohm-cm		
	150		bulk, $n = 10^{19}/cc$, $\rho = .005$ ohm-cm	300°K	21023

BISMUTH TELLURIDE

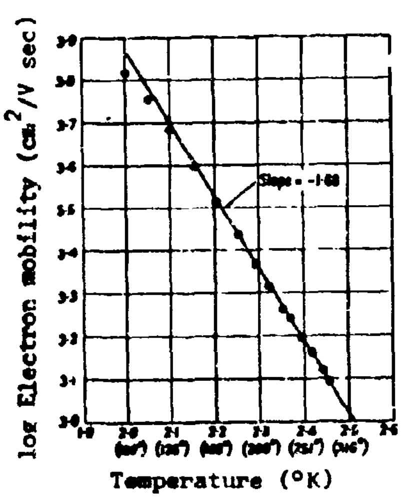
MOBILITY

Electron Hall mobility as a function of temperature in tellurium-doped, single crystal, n-type bismuth telluride. Samples designated by solid symbols are more homogeneous.

	n, cm^{-3}
△	$2/4\times10^{17}$
□	5.3×10^{17}
▲	3.0×10^{18}
◇	3.4×10^{18}
○	-
●	1.2×10^{19}
■	6.8×10^{19}



[Ref. 14854]



Electron mobility as a function of temperature in single crystal, n-type Bi_2Te_3, cut parallel to (0001) cleavage plane. $n_{77K} = 4.8\times10^{18}$/cc.

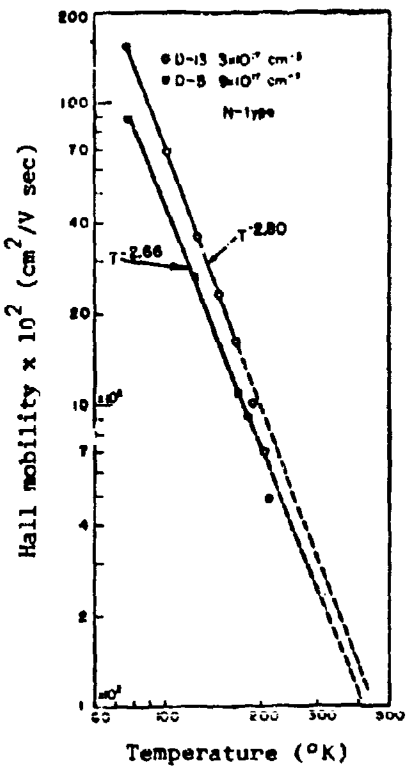
$$\mu_n = 1.67\times10^7\ T^{-1.68} \text{ (from 150-300°K)}$$

[Ref. 2360]

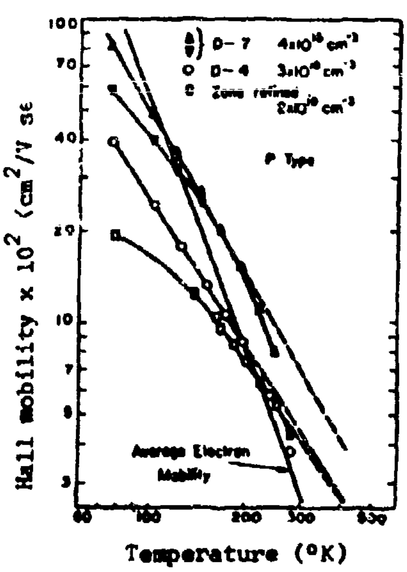
BISMUTH TELLURIDE

MOBILITY

Hall mobility as a function of temperature in n-type, single crystal bismuth telluride. The Hall coefficient was measured with the current parallel to cleavage plane and magnetic field perpendicular to cleavage plane. The resistivity was measured parallel to the cleavage plane.



[Ref. 801]

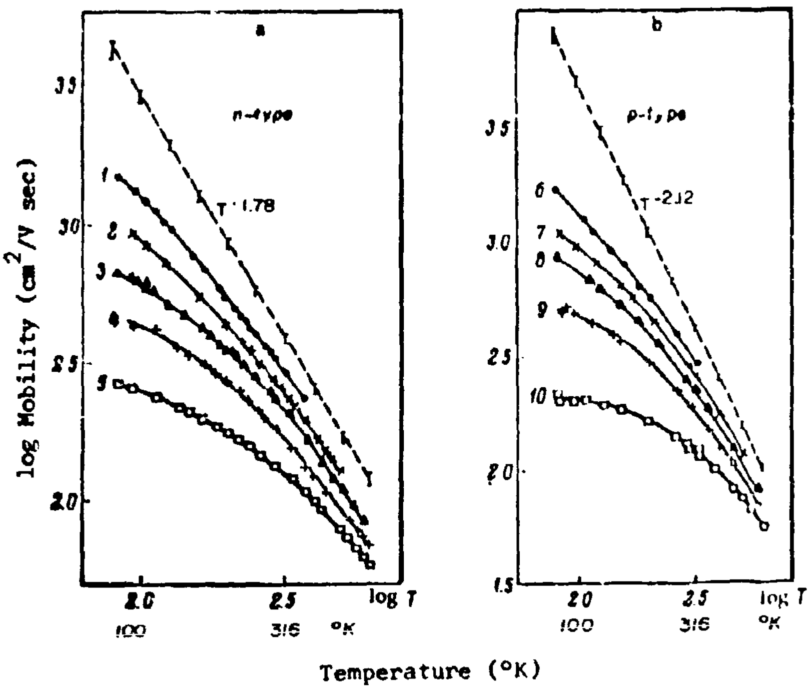


Hall mobility as a function of temperature for p-type, single crystal bismuth telluride. The Hall coefficient was measured with the current parallel to the cleavage plane and the magnetic field perpendicular to the cleavage plane. The resistivity was measured parallel to the cleavage plane (0001). D-7 was very inhomogeneous.

[Ref. 801]

BISMUTH SELENIDE

MOBILITY



Mobility as a function of log temperature in polycrystalline Bi_2Te_3. n-Type is CuBr-doped, p-type is Pb-doped.

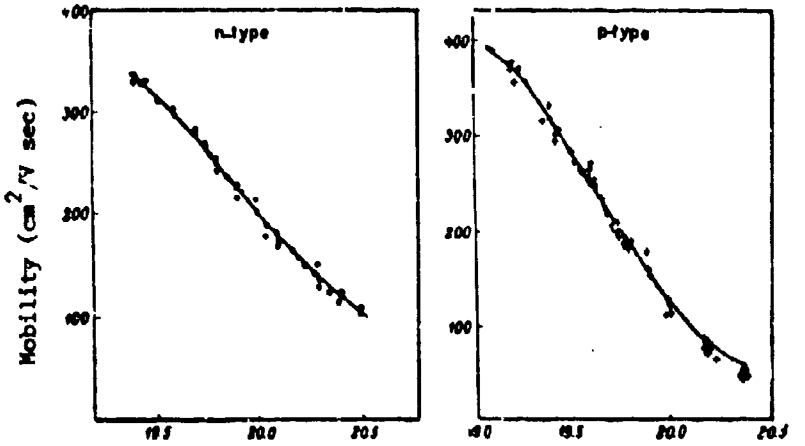
——— experimental
------ calculated to include impurity scattering

n-type, n, cm^{-3}	p-type, n, cm^{-3}
1) 2.5×10^{19}	6) 2.2×10^{19}
2) 5.2×10^{19}	7) 3.4×10^{19}
3) 7.8×10^{19}	8) 4.4×10^{19}
4) 12.3×10^{19}	9) 6.0×10^{19}
5) 20.4×10^{19}	10) 10.0×10^{19}

[Ref. 14525]

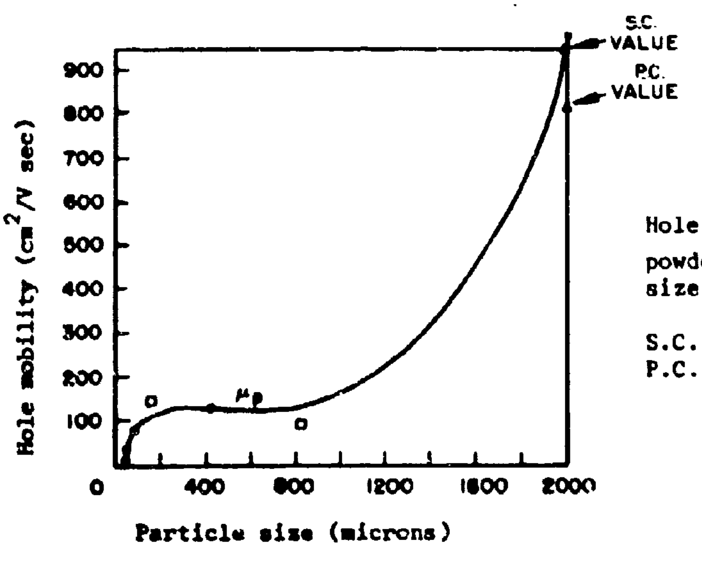
BISMUTH TELLURIDE

MOBILITY



Mobility as a function of carrier concentration at 300°K for polycrystalline Bi_2Te_3, $n > 10^{19}$/cc. Calculated curve includes impurity scattering; measured values of mobility are points on curve.

[Ref. 14525]



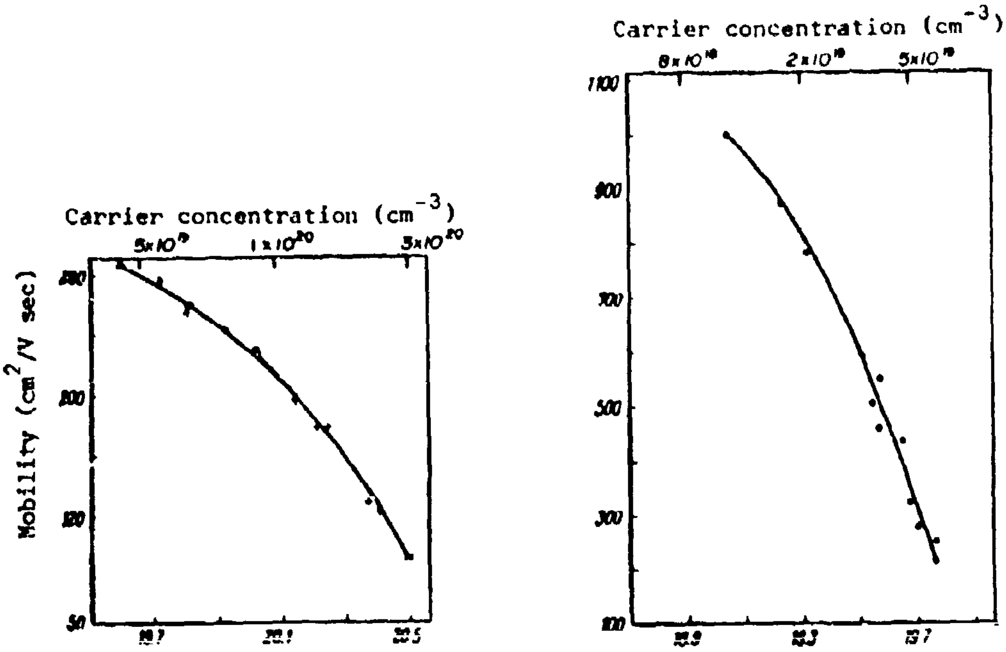
Hole mobility of pressed Bi_2Te_3 powders as a function of particle size at 77°K.

S.C. is single crystal value
P.C. is polycrystalline value.

[Ref. 8758]

BISMUTH TELLURIDE and BISMUTH SELENIDE

MOBILITY



log Carrier concentration (cm^{-3})

Bismuth Telluride   Bismuth Selenide

Mobility as a function of carrier concentration in polycrystalline, hot-pressed bismuth telluride and bismuth selenide, both n-type, at 300°K.

[Ref. 14675]

AIR FORCE MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND

EPIC

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BISMUTH SELENIDE

MOBILITY

Electron mobility as a function of temperature in single crystal, n-type Bi_2Se_3, measured parallel (0001) cleavage plane. Individual sample specifications are not given, only a range of all samples at 300°K.

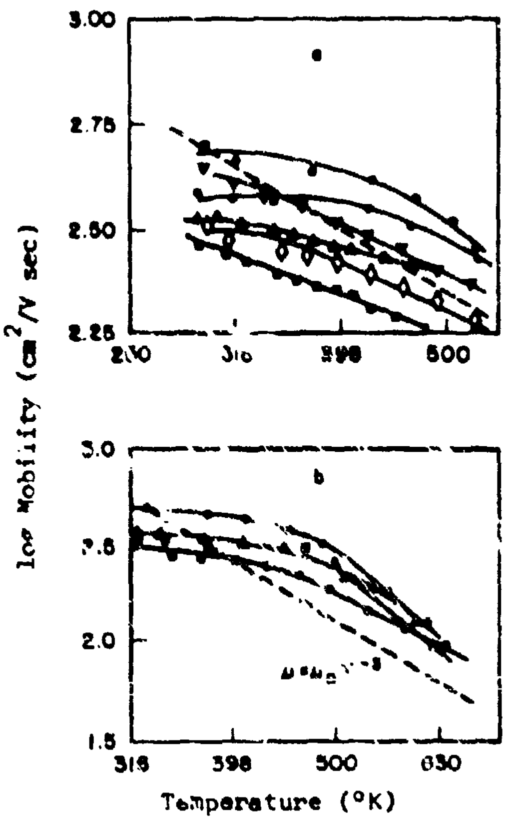
$n = 2\text{-}4 \times 10^{19}$/cc.

a) Electrical conductivity at 300°K ranges from 2000-3000 $(\text{ohm-cm})^{-1}$.

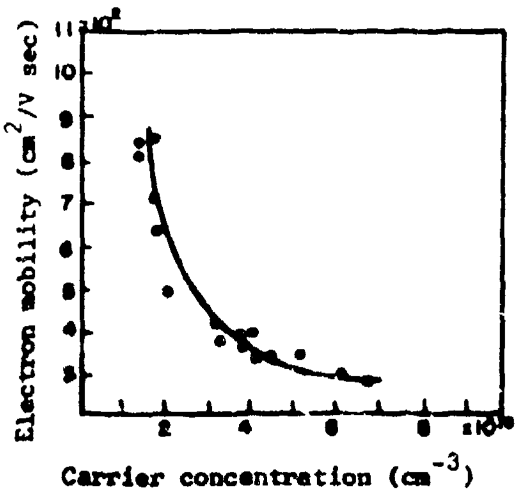
• This sample has conductivity of 1000 $(\text{ohm-cm})^{-1}$.

b) Electrical conductivity at 300°K is ∿ 2000 ohm-cm.

--- $\mu = \mu_o T^{-3}$.

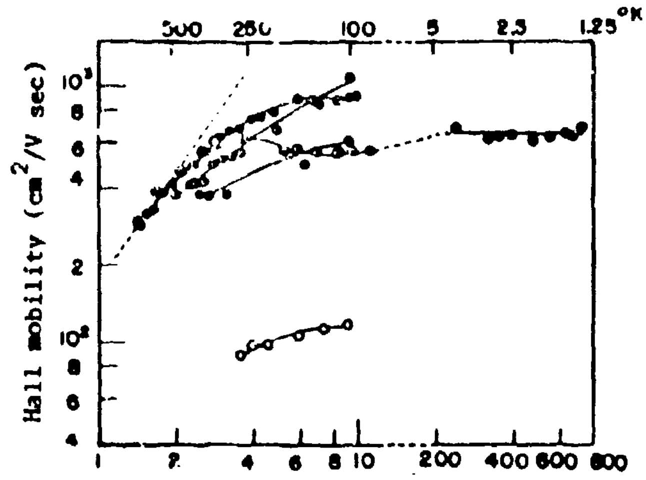


[Ref. 630]



Electron mobility as a function of carrier concentration in single crystal, n-type Bi_2Se_3 at 300°K.

[Ref. 630]



Hall mobility as a function of reciprocal temperature for single crystal, n-type Bi_2Se_3.

Sample No.		ρ (ohm-cm)	n, cm^{-3}
● 5		5.66×10^{-3}	2.44×10^{18}
● 6-13	normal	5.98	2.5
○ 6-13	parallel	25.5	3.3
● 6-14		13.55	0.598
● 6-14-1		14.2	0.74

---- $\mu = \mu_o T^{-1.5}$

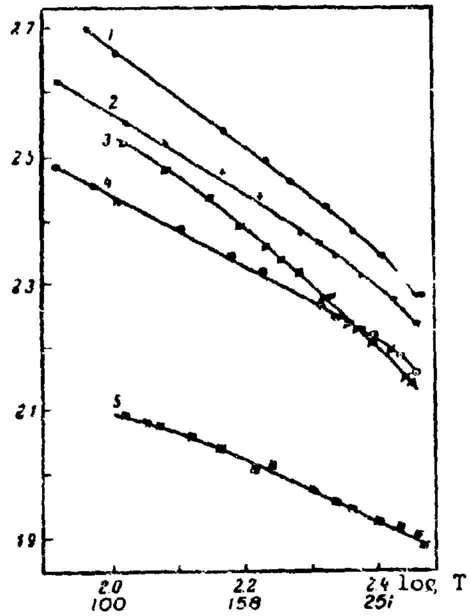
[Ref. 3097]

BISMUTH TELLURIDE-BISMUTH SELENIDE

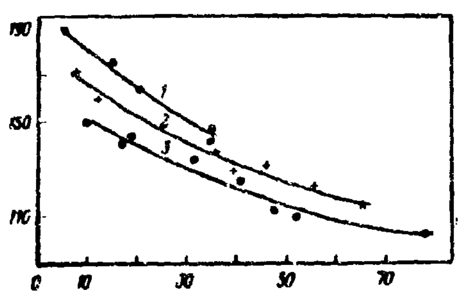
MOBILITY

Mobility as a function of temperature for hot-pressed polycrystalline, n-type Bi_2Te_3(80%)-Bi_2Se_3(20%). The solid solution is highly homogeneous. Samples are copper and lead doped.

	n, cm^{-3}
1)	4.6×10^{19}
2)	5.0×10^{19}
3)	8.0×10^{19}
4)	3.6×10^{20}
5)	5.5×10^{20}



[Ref. 14675]



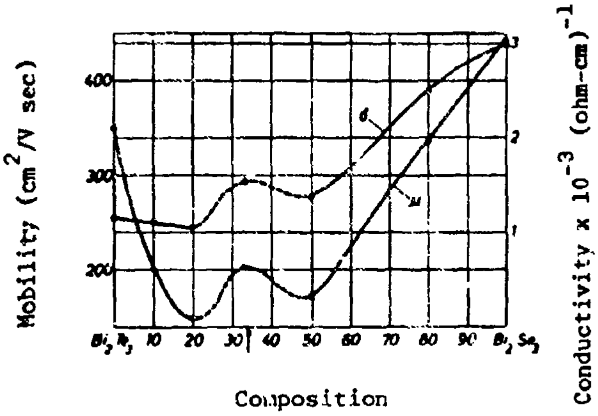
Mobility as a function of carrier concentration for hot-pressed polycrystalline, n-type, 80% Bi_2Te_3 + 20% Bi_2Se_3, with Cu and Pb doping.

	n, cm^{-3}
1)	5×10^{19}
2)	8×10^{19}
3)	1.1×10^{20}

[Ref. 14675]

BISMUTH TELLURIDE-BISMUTH SELENIDE

MOBILITY

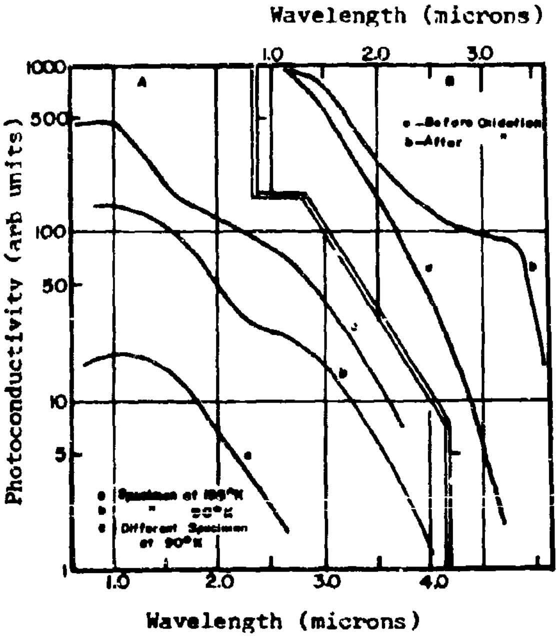


Mobility as a function of composition in polycrystalline Bi_2Te_3-Bi_2Se_3, silver iodide-doped. Carrier concentration for the Bi_2Te_3 = $2x10^{19}$/cc, increases to 4, then $5x10^{19}$ for the 5 compounds, and returns to $4.7x10^{19}$ for the Bi_2Se_3.

[Ref. 3867]

BISMUTH TELLURIDE

PHOTOELECTRONIC PROPERTIES



Photoconductivity as a function of wavelength in Bi_2Te_3, p-type films.
ρ = 1 ohm-cm
A) shows data taken at two temperatures

B) shows data taken before and after oxidation

Oxygen impurity centers introduce a photoconductive absorption band at about 0.44 eV,(2.8μ).

[Ref. 21299]

BISMUTH TELLURIDE and BISMUTH SELENIDE

PIEZOELECTRIC PROPERTIES (π)

Symbol	Value (cm^2/dyne)	Sample (single crystal)	Temperature	Ref.
	Bi_2Te_3			
π_{11}	$+87 \times 10^{-12}$	p-type, $n = 5 \times 10^{19}$/cc $p = 10^{13}$/cc	300°K	16428
$\pi_{33} + \pi_{31}$	-40×10^{-12}	"	"	16428
π_{33}	$+118 \times 10^{-12}$	n-type	300°K	5842
	+115			
	+90			
	Bi_2Se_3			
π_{11}	-2 to -5×10^{-12}	n-type, $\sigma = 3300$ (ohm-cm)$^{-1}$	78-300°K	5842

π_{11} is measured parallel to (0001)

π_{33} and π_{31} are measured normal to (0001)

See page 38 for additional information on piezocoefficient of resistivity.

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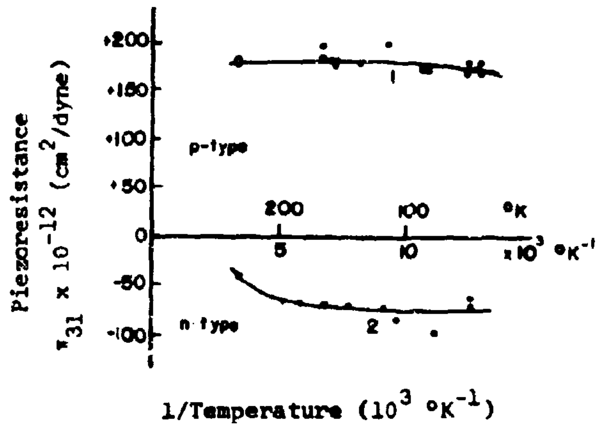
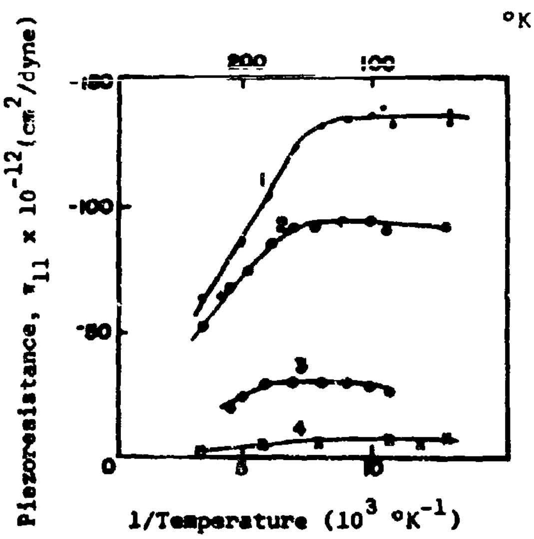
BISMUTH TELLURIDE and BISMUTH SELENIDE

PIEZOELECTRIC PROPERTIES

Temperature dependence of the piezoelectric constant π_{31} in single crystal, p-, and n-type Bi_2Te_3. Data is taken normal to (0001).



[Ref. 5842]



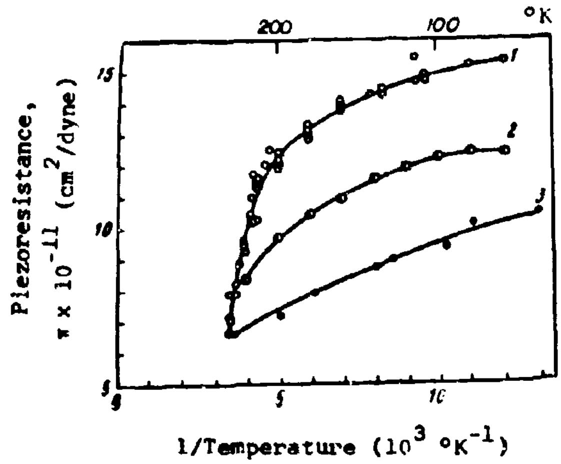
Temperature dependence of the piezoresistance coefficient π_{11} of single crystal, n-type Bi_2Te_3. The initial conductivity is given in $(ohm\text{-}cm)^{-1}$. All measurements are parallel to (0001).

1) 340 $(ohm\text{-}cm)^{-1}$
2) 720 "
3) 3500 "
4) is n-type, single crystal Bi_2Se_3, σ = 3300 $(ohm\text{-}cm)^{-1}$

[Ref. 5842]

BISMUTH TELLURIDE

PIEZOELECTRIC PROPERTIES



The piezoresistance coefficient π_{11}, in the glide plane, as a function of reciprocal temperature for three, single crystal, p-type Bi_2Te_3 samples.

1) σ = 170 $(\text{ohm-cm})^{-1}$
2) " 480 "
3) " 990 "

$\pi = \delta\rho/\rho \times \frac{1}{\chi}$, ρ = resistivity in (0001), χ = mechanical stress

[Ref. 3004]

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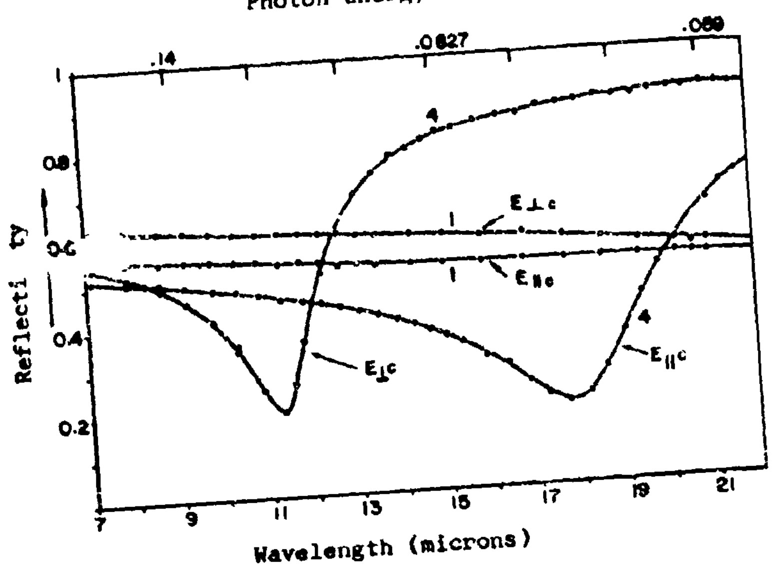
BISMUTH TELLURIDE

REFLECTION COEFFICIENT (R)

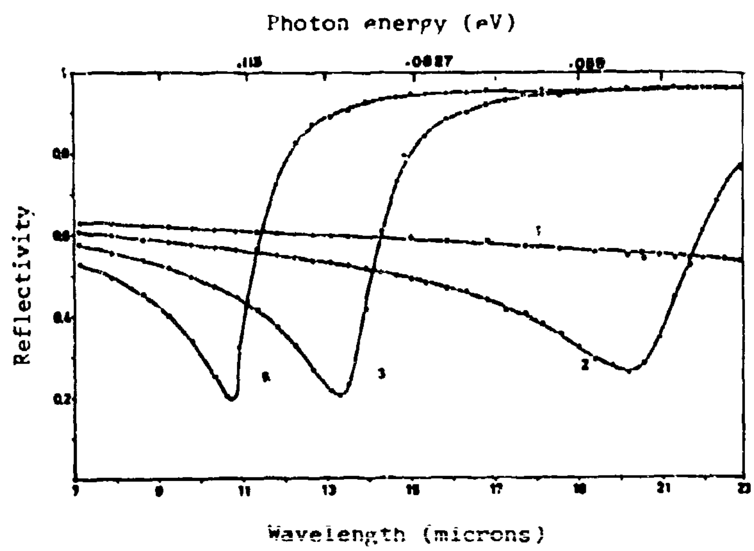


Reflectivity as a function of wavelength for single crystal, n-type Bi_2Te_3 at 78°K. Polarized light normal and parallel to (0001) cleavage plane is indicated. Sample 1 is lightly doped, $n = 9.5 \times 10^{18}$/cc; sample 4 is heavily doped, $n = 10^{20}$/cc.

[Ref. 18221]

BISMUTH TELLURIDE

REFLECTION COEFFICIENT



Reflectivity as a function of wavelength for variously doped single crystal, n-type Bi_2Te_3, at 78°K and parallel (0001) plane.

n at 293°K

1) 9.5×10^{18}/cc
2) 2.8×10^{19}
3) 6.8×10^{19}
5) 1.4×10^{20}

Increase in carrier concentration displaces reflectivity minima towards shorter wavelength.

[Ref. 18721]

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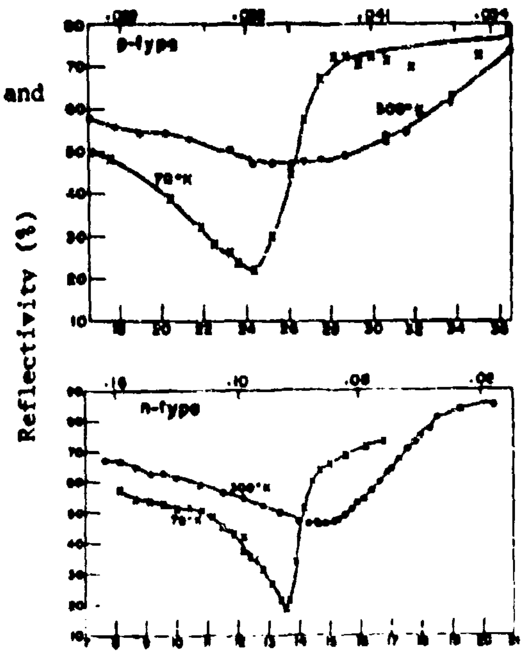
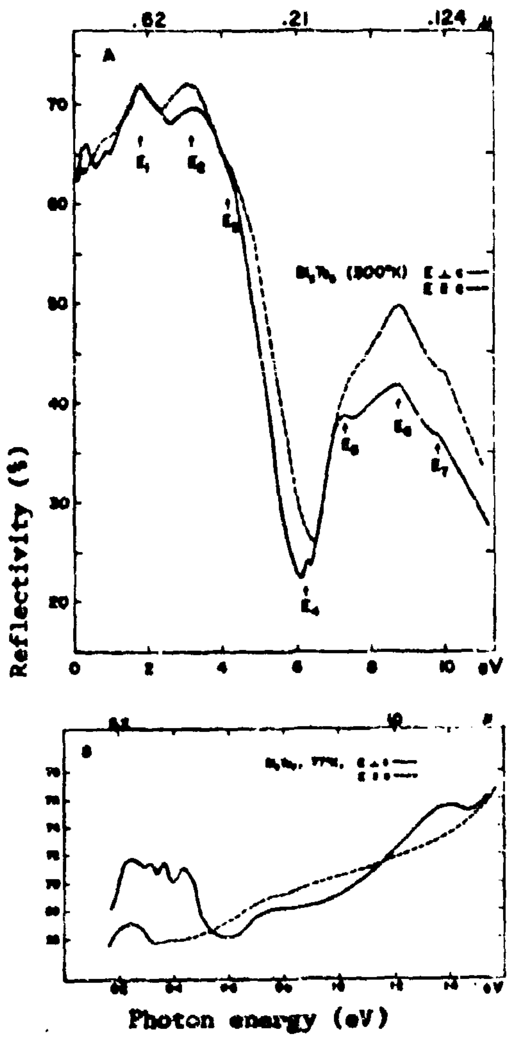
BISMUTH TELLURIDE

REFLECTION COEFFICIENT

Reflectivity as a function of wavelength for n-, and p-type single crystal Bi_2Te_3 at 78°K and 300°K.



[Ref. 21115]



Reflectivity as a function of photon energy for single crystal, p-type Bi_2Te_3

—— radiation normal to (0001) cleavage plane
--- radiation parallel to (0001) cleavage plane

A) λ = .113 to 12.4μ, 300°K
B) λ = .827 to 6.89μ, 77°K

[Ref. 22468]

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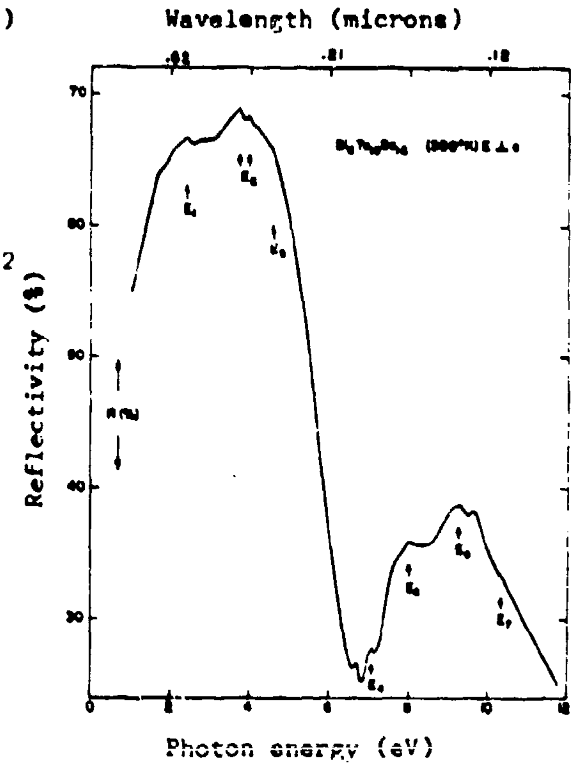
BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

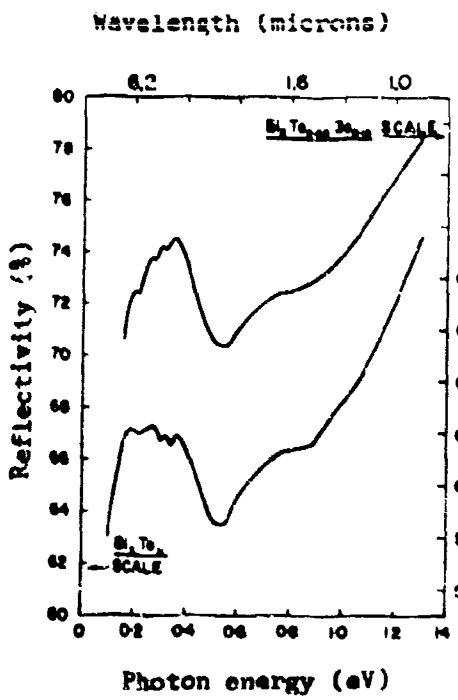
REFLECTION COEFFICIENT

Reflection coefficient as a function of photon energy for polycrystalline $Bi_2Te_{1.8}Se_{1.2}$ at 300°K. Radiation normal to (0001) cleavage plane, ($E_{\perp c}$).

(see table on next page for peak energies)



[Ref. 22468]



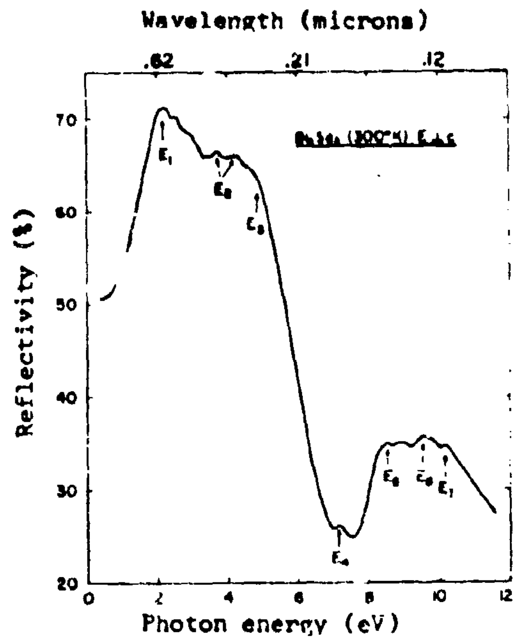
Reflection coefficient as a function of photon energy for single crystal, p-type Bi_2Te_3 and polycrystalline, p-type $Bi_2Te_{2.85}$-$Se_{0.15}$ at 300°K. Radiation normal to (0001) cleavage plane ($E_{\perp c}$).

[Ref. 22468]

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

REFLECTION COEFFICIENT

Reflection coefficient as a function of photon energy for single crystal, n-type Bi_2Se_3 at 300°K. Radiation is normal to (0001) cleavage plane, ($E_{\perp c}$).



[Ref. 22468]

mol% Bi_2Se_3 in Bi_2Te_3	E_1	E_2		E_3	E_4	E_5	E_6	E_7
0	1·78	3·23		4·20	6·29	7·34	8·72	9·80
5	1·87	3·30		4·30	6·39	7·47	8·79	9·88
10	1·95			4·33	6·50	7·63	8·87	
20	2·14	3·80		4·41	6·66	7·67	9·10	
30	2·33	3·94		4·60	6·97	8·06	9·23	10·0
40	2·28	3·79	3·90	4·57	7·10	8·20	9·49	10·14
50	2·28	3·75	3·99	4·60	7·05	8·16	9·45	
60	2·34	3·73	4·02	4·70	7·20	8·30	9·45	10·24
70	2·33	3·73	4·27	4·74	7·20	8·18	9·45	
80	2·29	3·73	4·18	4·83	7·14	8·25	9·37	
90	2·34	3·73	4·19	4·85	7·11	8·26	9·45	
100	2·34	3·73	4·24	4·87	7·20		9·45	10·16

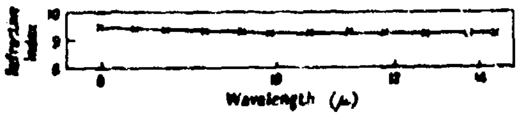
Bi_2Te_3 and Bi_2Se_3 are single crystals. The alloys are polycrystalline. Peaks for 2 alloys are shown graphically on this page and the preceding one.

[Ref. 22468]

BISMUTH TELLURIDE

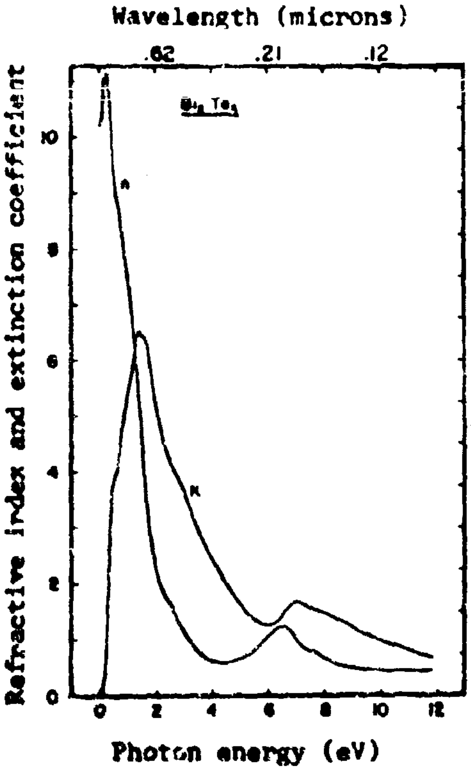
REFRACTIVE INDEX (n)

Symbol	Value	Sample	Wavelength	Temperature	Ref.
n	9.2	single crystal, n-type (0001)	8-14μ	300°K	3124



Refractive index as a function of wavelength for single crystal, n-type Bi_2Te_3, iodine-compensated intrinsic. Data taken on a (0001) cleavage plane at 118°K.

[Ref. 3124]



Refractive index, n, and extinction coefficient, k, as a function of photon energy in single crystal, p-type Bi_2Te_3. Radiation normal to cleavage plane, (0001), $E_{\perp c}$.

[Ref. 22468]

No refractive index data available for Bi_2Se_3.

BISMUTH TELLURIDE

THERMAL CONDUCTIVITY (κ)

Symbol	Value (W/cm deg)	σ (ohm-cm)$^{-1}$	Sample (single crystal)	Temperature	Ref.
k	.0316	2700	n-type, impurity, parallel (0001)	150°K	2678
	.0187	730	" " "	300°K	
	.0278	370	n-type, near intrinsic, "	150°K	
	.0244	200	" " "	300°K	2678
k_L	.0268		n-, and p-type, single crystals	150°K	2421
	.0157		or aligned polycrystalline	300°K	2421

	p-type	n-type	parallel (0001),		
k	.072	.066	n-type, σ = 6.3x10^3 (ohm-cm)$^{-1}$	77°K	3215
k_e	.01	.011	for .09% iodine-doped		
k_L	.06	.055	p-type, σ ∿ 6x10^3 (ohm-cm)$^{-1}$		
			for undoped material		3215

k	.0034	p-type, ρ = .13x10^{-2} ohm-cm	517°K	2401
	.004	ρ = .2x10^{-2} (hot-pressed)	628°K	2401

k = total thermal conductivity

k_e = electron thermal conductivity

k_L = lattice thermal conductivity

BISMUTH SELENIDE

THERMAL CONDUCTIVITY

Symbol	Value (W/cm deg)	Sample (single crystal)	Temperature	Ref.
k	.0077	p-type, ρ = $.58 \times 10^{-3}$ ohm-cm	374°K	2401
	.0053	.79	413°K	
	.0039	.98	511°K	
	.0047	$.13 \times 10^{-2}$	428°K	
	.0060	$.83 \times 10^{-3}$ (hot-pressed)	445°K	2401

BISMUTH TELLURIDE-BISMUTH SELENIDE

k (mW/cm °K)	k_e (mW/cm °K)	k_L (mW/cm °K)	% Composition Bi_2Te_3	% Composition Bi_2Se_3	Conductivity $(ohm\text{-}cm)^{-1}$				
19.8	3.3	16.5	100	0	729	n-type	single crystal, undoped	300°K	19825
16.1	2.7	13.4	95	5	591				
13.1	1.3	11.8	90	10	290				
11.9	0.9	11.0	77.78	16.67	206				
12.0	0.8	11.2	80	20					
15.6	0.4	15.2	66.67	33.33	84	n- and p-type			
14.4	1.4	13.0	50	50	315	p-type			
13.0	2.3	10.7	40	60	513				
14.5	3.8	10.7	33.33	66.67	833				
17.5	5.3	12.2	16.67	77.78	1182				
27.0	8.8	18.2	0	100	1953				19825

BISMUTH TELLURIDE

THERMAL CONDUCTIVITY

(Additional graphs will be found in Thermoelectric Properties)

Total thermal conductivity as a function of reciprocal temperature for two single crystal Bi_2Te_3 samples, together with representative data of Goldsmid [Ref. 2678].

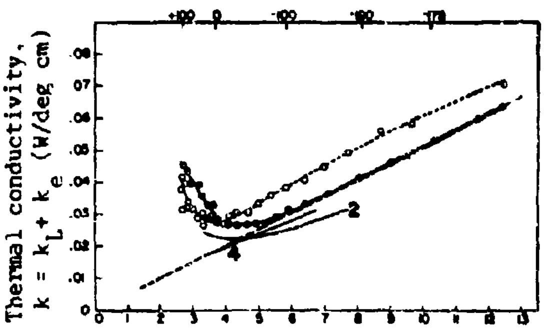
o single crystal, p-type, $n = 2x10^{19}$/cc (zone refined) (0001)

• n-type, $n = 3x10^{17}$/cc (0001)

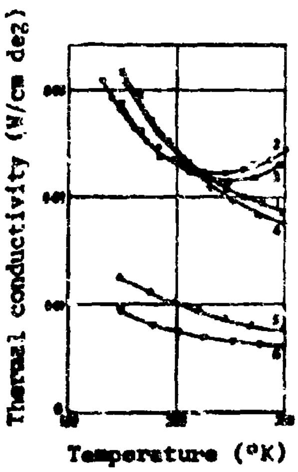
-- lattice thermal conductivity $= k_L$

k_e = electron thermal conductivity

	Type	Sample [Ref. 2678]
2	n	near intrinsic, ρ = .005 ohm-cm
4	p	parallel (0001), ρ = .002 ohm-cm



[Ref. 801]



Thermal conductivity as a function of temperature for single crystal Bi_2Te_3.

Sample		Type	ρ, ohm-cm	Orientation
1)	impure	n	.001	parallel (0001)
2)	near intrinsic	n	.005	"
3)	"	n	.005	"
4)	impure	p	.002	"
5)	"	p	.002	normal (0001)
6)	"	p	.002	"

[Ref. 2678]

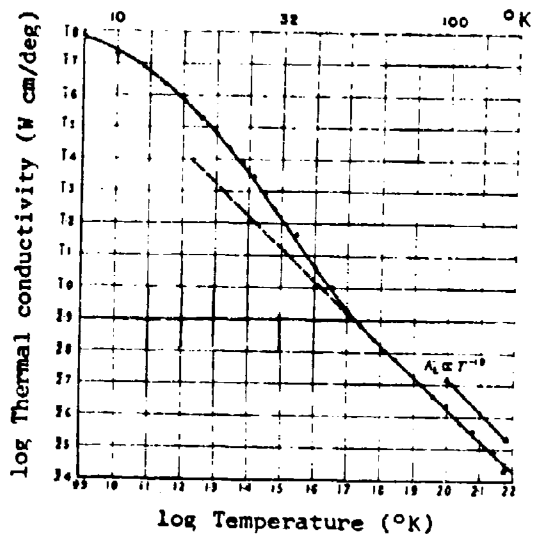
BISMUTH TELLURIDE

THERMAL CONDUCTIVITY

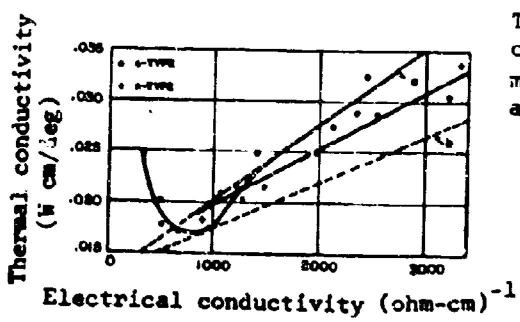
Lattice conductivity of stoichiometric single crystal, n- or p-type Bi_2Te_3 compared with data from Goldsmid and Ure for tellurium-doped samples. Temperature coefficient of lattice conductivity is given for temperatures over 100°K.

■ [Ref. 2421], 150-300°K

▲ [Ref. 801], 77-373°K



[Ref. 3466]



Thermal conductivity as a function of electrical conductivity in Bi_2Te_3, at 300°K. Samples are macrocrystalline, the p-type has excess bismuth and the n-type is CuI-doped.

--- t eoretical curves, calculated for thermal scattering (a) and degeneracy (b)

[Ref. 7768]

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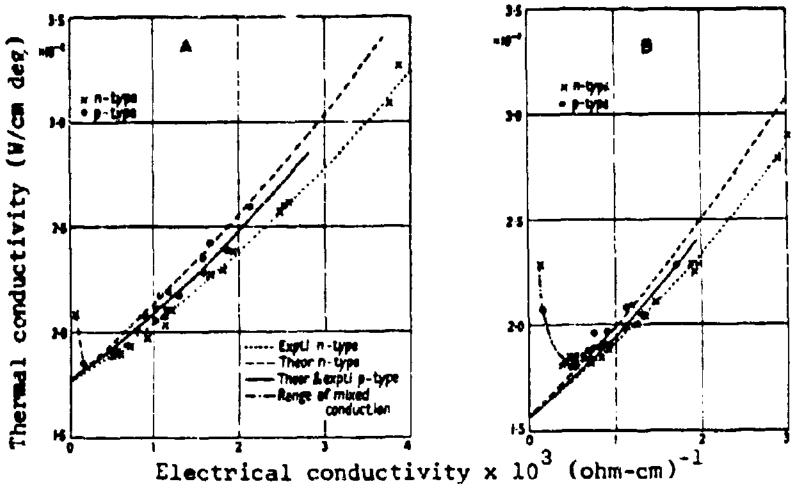
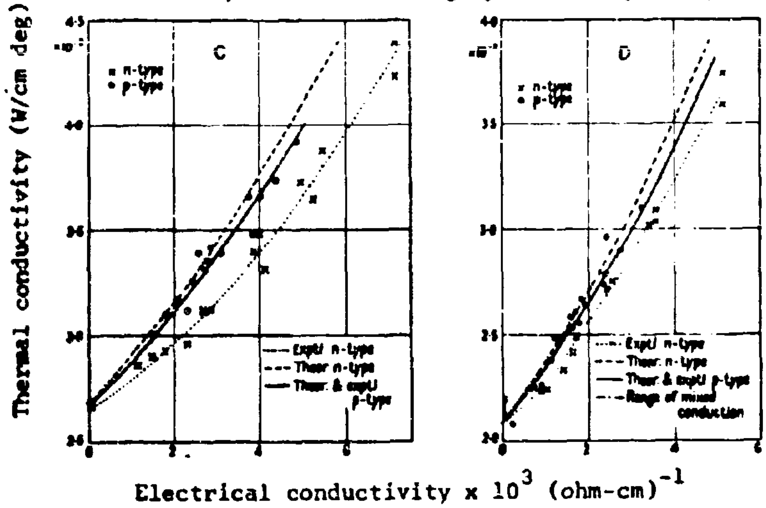
BISMUTH TELLURIDE

THERMAL CONDUCTIVITY



Thermal conductivity as related to electrical conductivity at 250°K (A) and 300°K (B). The single crystal, p-type samples were variously doped, the n-type are doped with iodine and chlorine only. The decrease in lattice thermal conductivity for the n-type material is due to additional phonon scattering by the halogen impurity.



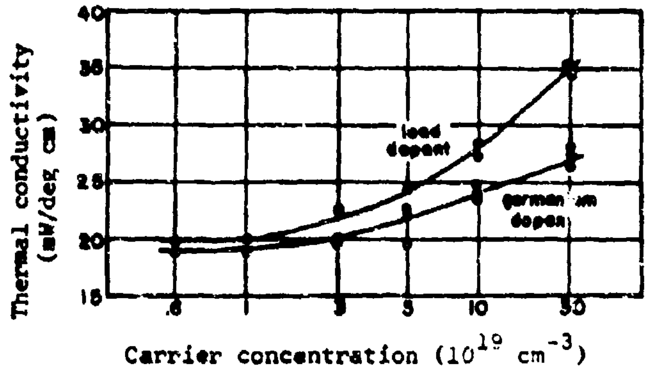
Thermal conductivity as related to electrical conductivity at 150°K (C) and 200°K (D).

[Ref. 2421]

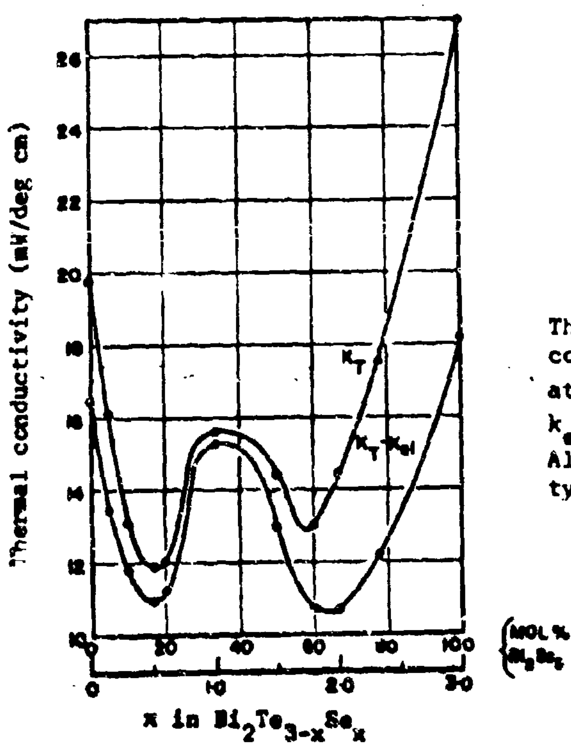
BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

THERMAL CONDUCTIVITY

Thermal conductivity as a function of carrier concentration for single crystal Bi_2Te_3 at 300°K. The samples are lead- and germanium-doped, lead yields p-type, germanium gives n-type.



[Ref. 16182]



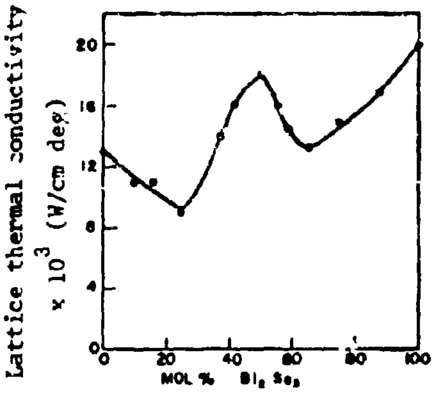
Thermal conductivity as a function of composition in the Bi_2Te_3-Bi_2Se_3 system at 300°K. k_T is thermal conductivity. k_{el} is electron thermal conductivity. All samples are polycrystalline, at x = 1 type changes from p to n.

[Ref. 19825]

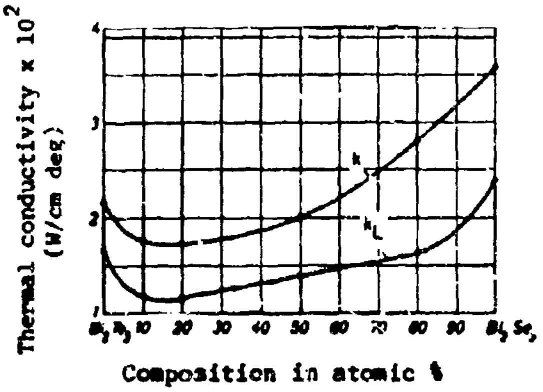
BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

THERMAL CONDUCTIVITY

Lattice thermal conductivity as a function of composition in the Bi_2Te_3-Bi_2Se_3 system. Samples are macrocrystalline, n-type, copper bromide-doped.



[Ref. 7768]



Thermal conductivity as a function of composition in the Bi_2Te_3-Bi_2Se_3 system at 300°K. Single crystal samples are 0.1% silver iodide-doped.

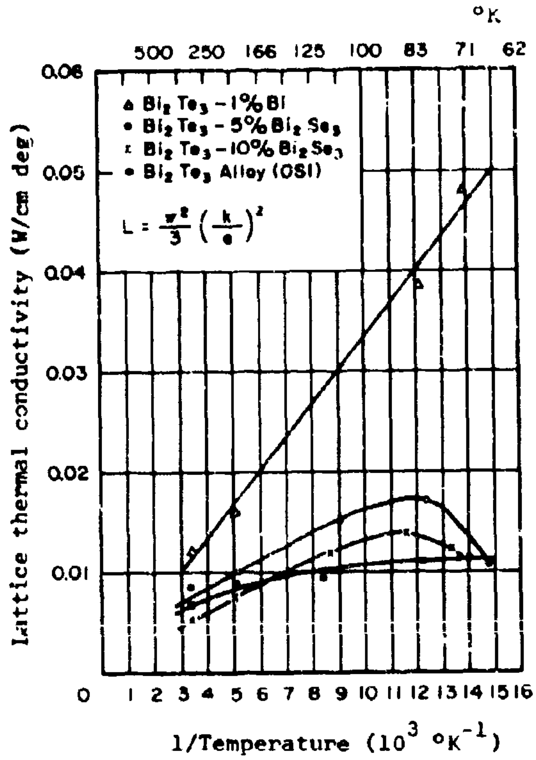
k = thermal conductivity
k_L = lattice thermal conductivity

Lack of data between 33 and 50% Bi_2Se_3 masks the anomalous behaviour seen in [Ref. 7768] and [Ref. 19825].

[Ref. 3867]

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

THERMAL CONDUCTIVITY



Thermal conductivity as a function of reciprocal temperature for several Bi_2Te_3-Bi_2Se_3 polycrystalline alloys.

□ commercial, n-type Bi_2Te_3

Δ p-type Bi_2Te_3 + 1% Bi_2Se_3

o n-type Bi_2Te_3 + 5% Bi_2Se_3 + .26% CuBr

x n-type Bi_2Te_3 + 10% Bi_2Se_3 + .26% CuBr

The electronic component of the thermal conductivity has been subtracted by assuming degenerate statistics and using the Wiedmann-Franz ratio.

[Ref. 15503]

BISMUTH TELLURIDE

THERMOELECTRIC PROPERTIES

Q (μV/°K)	σ (ohm-cm)$^{-1}$	k (W/cm deg)	Z (deg^{-1})	Sample	Temperature	Ref.
61	6.9×10^{3}	.072		single crystal, p-type,	77°K	3215
68	5.85	.072		undoped, parallel (0001)		
-139	1.71	.058		single crystal, n-type		
-73	6.3	.066		with increasing I-doping		
-22	15.2	.076				3215

Q (μV/°K)	σ (ohm-cm)$^{-1}$	k (W/cm deg)	Z (deg^{-1})	macrocrystalline Doping wgt. %	n (10^{19} cm^{-3})	Temperature	Ref.
+240	5.25×10^{2}	.0200	1.51×10^{-3}	undoped	(1.23)	300°K	3867
+242	3.05	.0215	0.83	AgI 0.01	-		
+ 13	3.50	-	-	AgI 0.03	-		
-202	11.50	.0216	2.18	AgI 0.10	2.05		
-177	15.40	.0230	2.10	AgI 0.15	2.8		
-148	21.00	.0248	1.86	AgI 0.20	3.83		
-73	53.20	-	-	AgI 1.00	18.2		
+184	7.74	.0207	1.26	Sn 0.1	3.25		
+10[illegible]	8.85	.0210	0.47	Sn 0.3	10.35		
+ 55	10.00	-	-	Sn 0.5	33.4		3867

Q (μV/°K)	σ (ohm-cm)$^{-1}$	k (W/cm deg)	Z (deg^{-1})	Sample	Temperature	Ref.
+200	500	.0175	1.14×10^{-3}	impure single crystal, p-type,	300°K	2678
-215	750	.019	2.81	n-type		
-200	200	.024	2.50	pure, n-type		2678

All measurements parallel (0001)

Q (thermal e.m.f); σ (electrical conductivity); Z (figure of merit); k (thermal conductivity); n (carrier concentration)

BISMUTH TELLURIDE

THERMOELECTRIC PROPERTIES

Q (max)	σ $(ohm\text{-}cm)^{-1}$	k (W/cm deg)	Z (300K)	n, cm^{-3}	Sample single crystal	Temperature	Ref.
180	500	.021	>0.048	5×10^{18}	n-type, excess Te	333°K	2624
170	400		>0.041	8×10^{18}	p-type, excess Bi or Pb	333°K	
210	300					300°K	2624

BISMUTH SELENIDE

-100	2000	∿ .03	$.66\times10^{-3}$	2×10^{19}	n-type	300°K	2866
-51	2000			23×10^{18}	single crystal	300°K	21836
-41	650			23×10^{18}	$Bi_{1.86}In_{0.14}Se_3$ macrocrystalline	300°K	21836

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BISMUTH TELLURIDE-BISMUTH SELENIDE

THERMOELECTRIC PROPERTIES

Bi_2Te_3	Bi_2Se_3	Q (μV/°C)	σ (ohm-cm)$^{-1}$	k (W/cm °C)	Z (deg^{-1})	Ref.
100%	0	+ 212	729	.0198	1.66×10^{-3}	19825
95	5	+ 231	591	.0161	1.96	
90	10	+ 273	290	.0131	1.65	
83.33	16.67	+ 290	206	.0119	1.46	
80	20	+ 284	180	.0120	1.20	
66.67	33.33	∿ 0	84	.0156	0	
50	50	- 228	315	.0144	1.14	
40	60	- 180	513	.0130	1.28	
33.33	66.67	- 135	833	.0145	1.05	
22.32	77.78	- 109	1182	.0175	0.80	
0	100	- 70	1953	.0270	0.35	19825

The above values are for macrocrystalline samples at 300°K.

100	0	+ 240	525	.0[illegible]	1.[illegible]1x10^{-3}	3867
80	20	+ 90	263	-	-	
66.67	33.33	- 213	262	.0142	.[illegible]4	
50	50	- 163	486	.0158	.82	
25	75	- 87	1814	.0199	84	
0	100	- 60	2330	.0304	.28	

The above values are for macrocrystalline samples at 300°K.

100	0	- 202	1148	.0216	2.[illegible]6x10^{-3}	
90	10	- 179	1335	.0175	1.[illegible]8	
80	20	- 177	975	.0174	1.[illegible]7	
66.67	33.33	- 1[illegible]	1560	-	1.[illegible]9	
50	50	- 105	1440	.02[illegible]3	0.[illegible]5	
20	80	- 53	2730	.[illegible]2[illegible]9	0.27	
0	100	- 44	333[illegible]	.03[illegible]7	0.16	3867

The above values are for silver iod[illegible] doped [illegible]croc[illegible]ystalline at 300°K.

BISMUTH TELLURIDE-BISMUTH SELENIDE

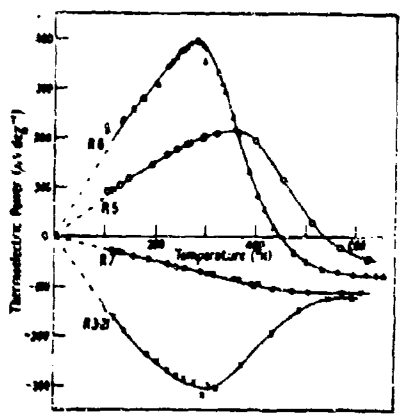
THERMOELECTRIC PROPERTIES

Bi_2Te_3	Bi_2Se_3	Q (μV/°C)	σ $(ohm\text{-}cm)^{-1}$	k (W/cm °C)	Z (deg^{-1})	Temperature	Ref.
90	10	- 200.1	1245	.0168		293.3°K	19515
		- 173.6	1838	.0228		271 °K	
		- 125.6	3495	.0398		115.9°K	19515

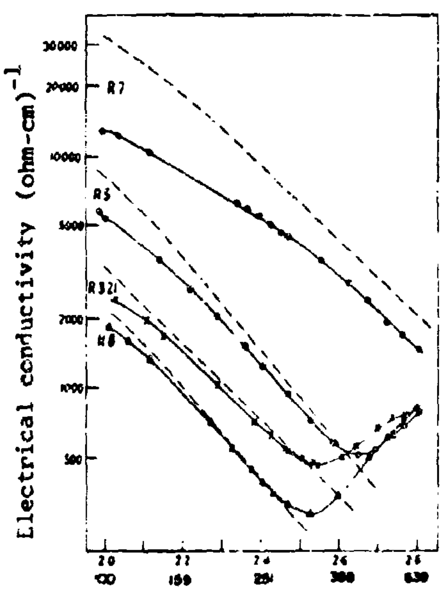
The above values are for a single crystal, n-type sample.

BISMUTH TELLURIDE

THERMOELECTRIC PROPERTIES



Temperature (°K)



Temperature (°K)

Electrical conductivity and thermoelectric emf as a function of temperature for Bi_2Te_3. Current flow parallel to cleavage plane (0001).

----- calculated curve
——— experimental

Sample	Type	Crystal
R 8	p	single crystal
R 5	p	macrocrystalline, zone refined
R 7	n	macrocrystalline, zone refined
R-3-21	n	macrocrystalline, zone refined

[Ref. 3223]

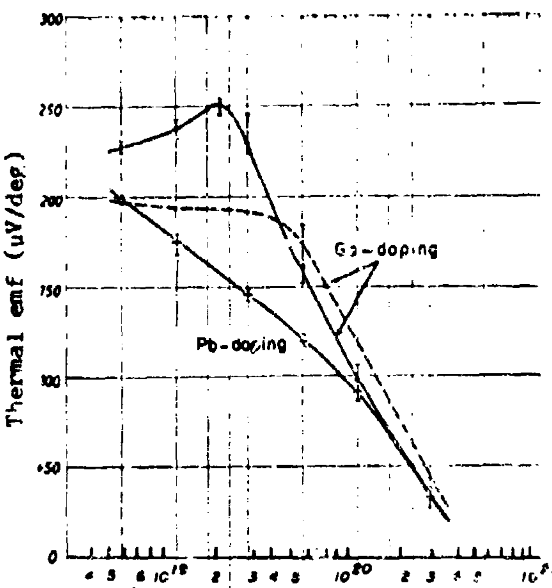
BISMUTH TELLURIDE

THERMOELECTRIC PROPERTIES

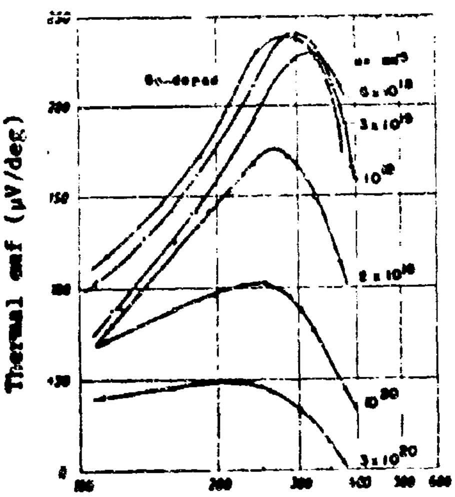
Thermal emf as a function of lead and germanium concentration in macro-crystalline Bi_2Te_3 at 300°K.

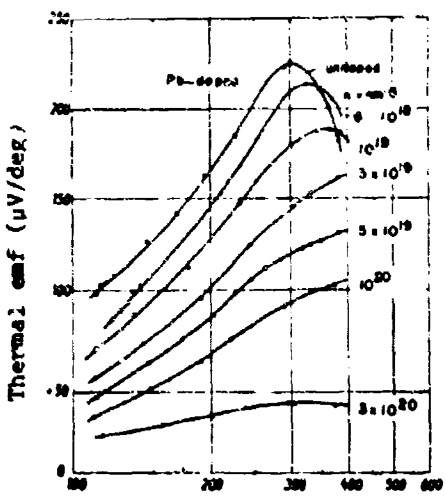
--- measurement taken immediately after sample preparation (Ge-doped)

—— measured about three months after sample preparation



[Ref. 15813]





Temperature (°K)

Thermal emf as a function of temperature for Pb-, and Ge-doped, p-type, macro-crystalline Bi_2Te_3, normal to (0001) cleavage plane. [Ref. 15813]

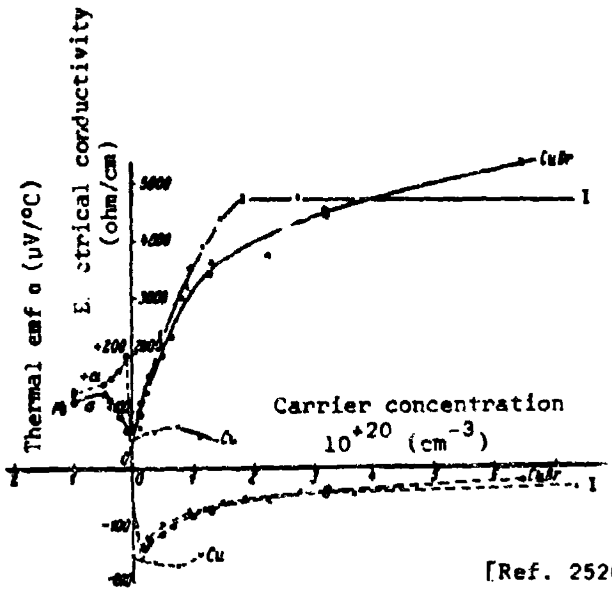
BISMUTH TELLURIDE

THERMOELECTRIC PROPERTIES

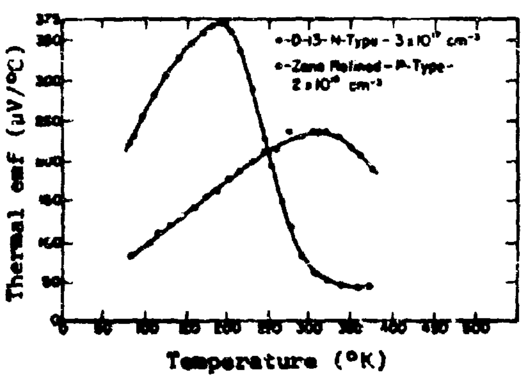
(---) Thermal emf and (—) electrical conductivity in polycrystalline Bi_2Te_3 as a function of carrier concentration at a range of 300-700°K. Lead additives yield p-type material; halides yield n-type samples. Copper must be added as a halide rather than the metal.

Maximum Values for Lead-doped Samples

σ = 1300 (ohm-cm)$^{-1}$
Q = 20_ μV/°K



[Ref. 2526]



Seebeck coefficient as a function of temperature for n-type, Te-doped, and p-type zone refined, single crystal bismuth telluride.

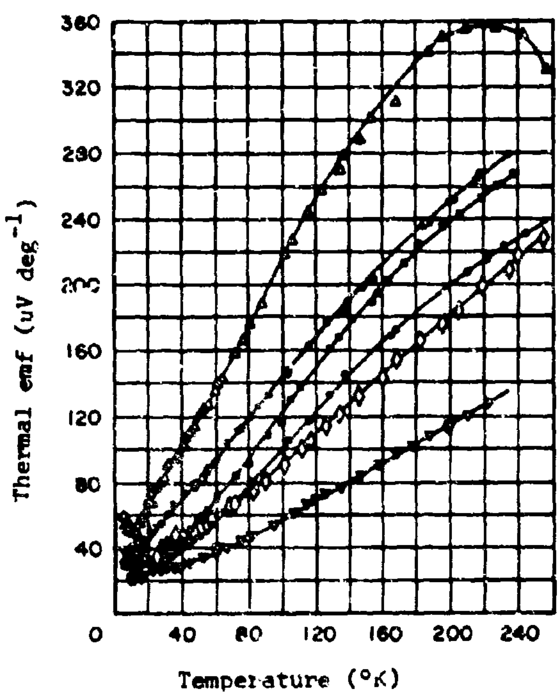
[Ref. 14854]

BISMUTH TELLURIDE

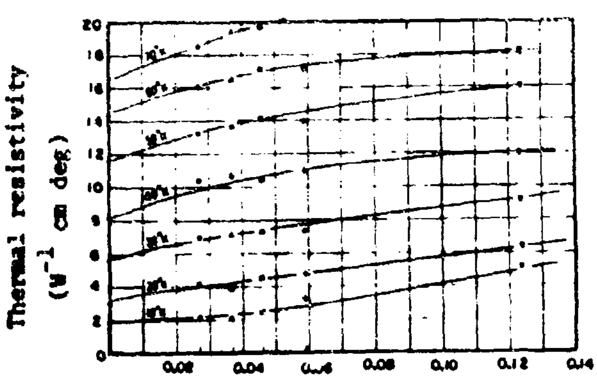
THERMOELECTRIC PROPERTIES

Thermoelectric emf as a function of temperature for single crystal, n-type, iodine-doped Bi_2Te_3, cut parallel to (0001) cleavage plane.

Symbol	Type	% Iodine
Δ	n	.037
□	n	.046
o	n	.059
∇	n	.124
●	p	.027
▲	p	undoped



[Ref. 3466]

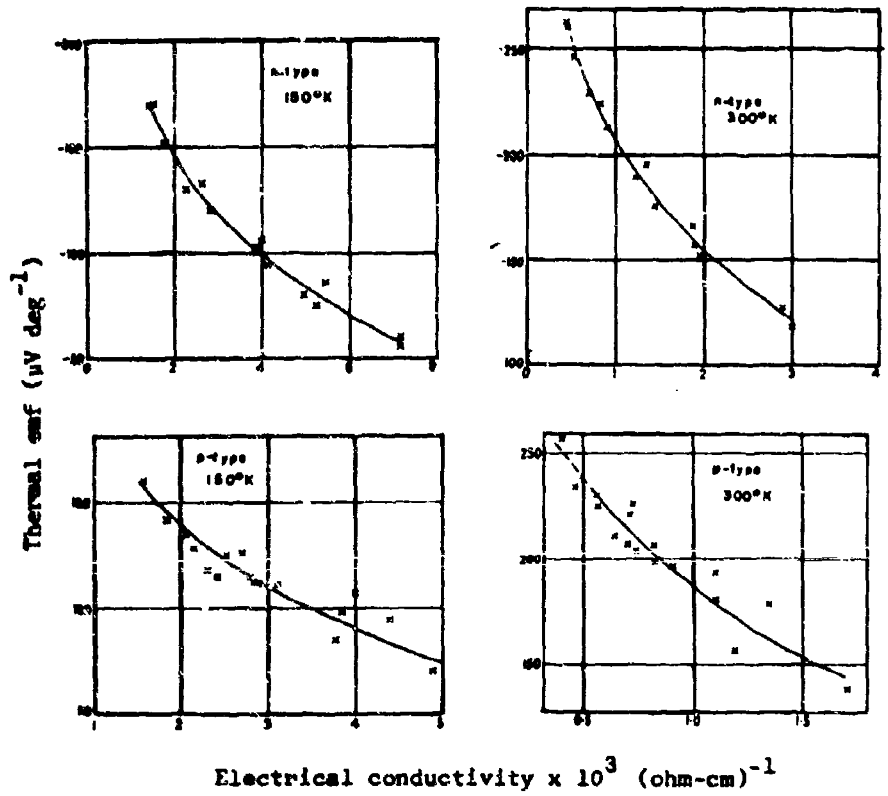


Thermal resistivity as a function of iodine doping at several temperatures for single crystal, n- or p-type Bi_2Te_3; iodine-doped sample cut parallel to (0001) cleavage plane.

[Ref. 3466]

BISMUTH TELLURIDE

THERMOELECTRIC PROPERTIES

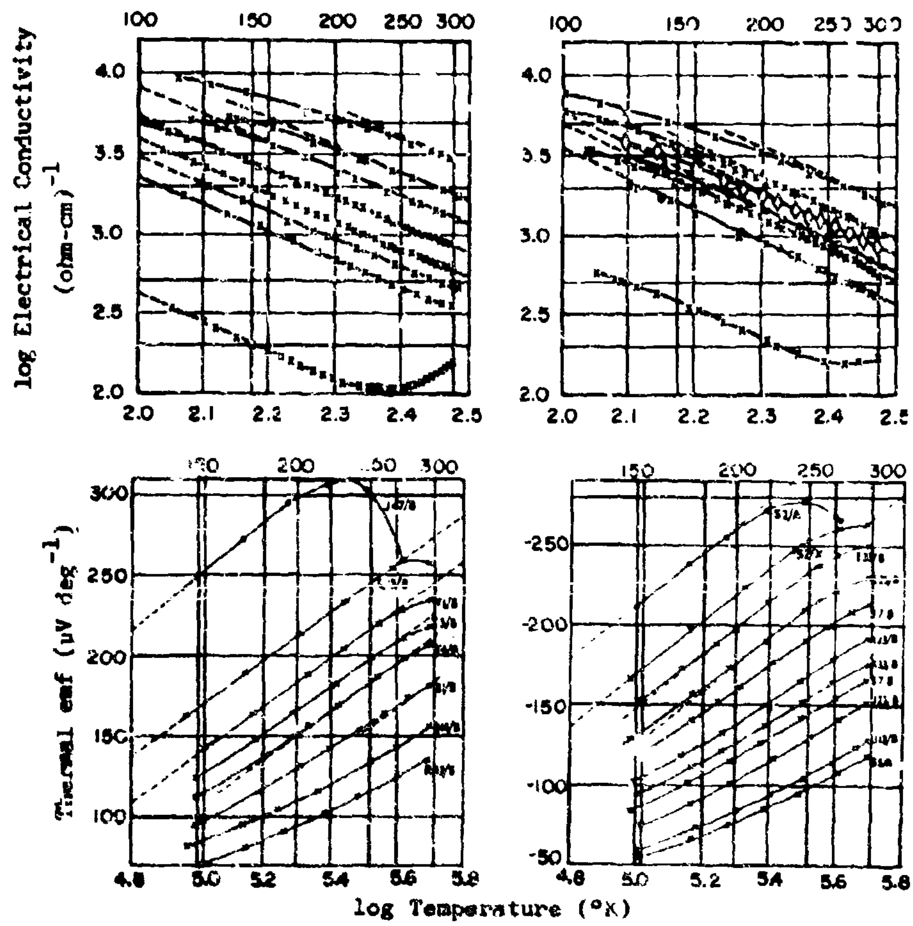


Thermal emf as related to conductivity for zone refined polycrystalline Bi_2Te_3. Type and temperature are shown on individual graphs. The p-type material is undoped, or with excess bismuth: $\rho \sim .002$ ohm-cm. The n-type is iodine-doped.

[Ref. 2595]

BISMUTH TELLURIDE

THERMOELECTRIC PROPERTIES

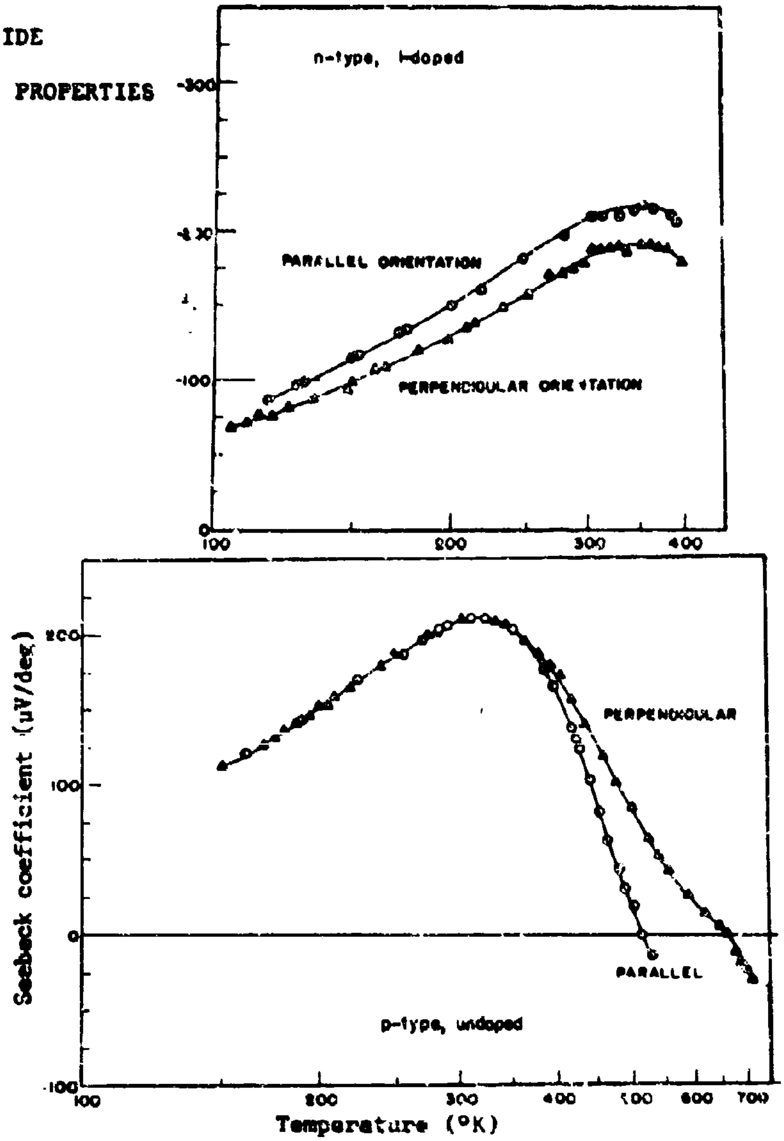


Log electrical conductivity and thermal emf as a function of log temperature for n-, and p-type Bi_2Te_3 samples. Specifications are not given, but may be either single or polycrystalline. Change in slope at higher temperatures is due to mixed conduction.

[Ref. 2595]

BISMUTH TELLURIDE

THERMOELECTRIC PROPERTIES



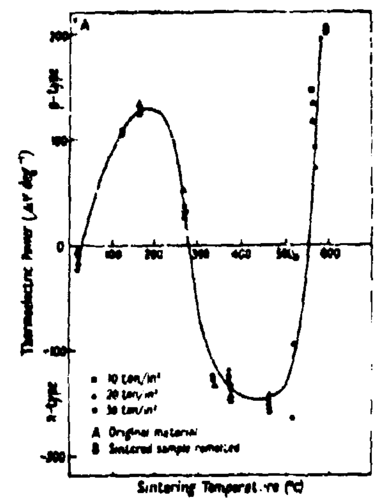
Seebeck coefficient as a function of temperature for two samples of single crystal Bi_2Te_3 taken parallel and normal to (0001) cleavage planes. The undoped material is seen to be isotropic at temperatures below the point at which mixed conduction begins.

[Ref. 19827]

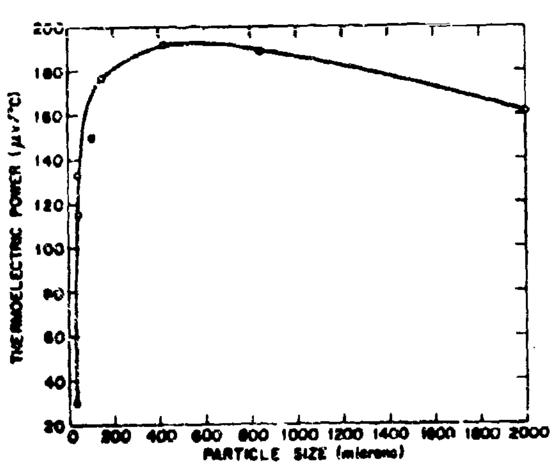
BISMUTH TELLURIDE

THERMOELECTRIC PROPERTIES

Thermal emf as a function of sintering temperature for p-type, zone refined Bi_2Te_3, iodine-doped. The material was crushed and compacted at various pressures, then sintered at temperatures up to melting point. Change in type is noted and reproducible; (10 ton/in^2 = 1406.14 kg/cm^2). Compacting pressure has only slight effect on thermal emf.



[Ref. 3585]



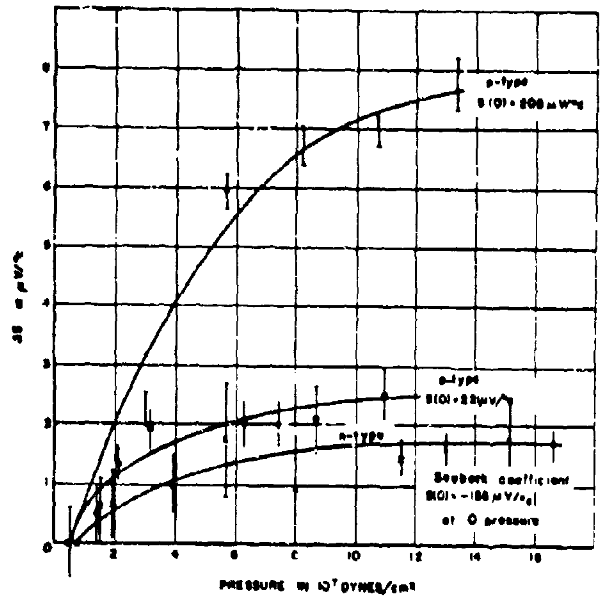
Thermal emf as a function of particle size in p-type Bi_2Te_3 powders at 300°K, $n \sim 2\times10^{19}$/cc.

[Ref. 8758]

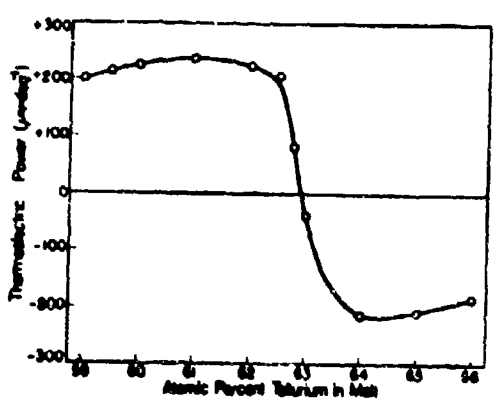
BISMUTH TELLURIDE

THERMOELECTRIC PROPERTIES

Changes in the Seebeck coefficient as a function of pressure at 300°K, in single crystal Bi_2Te_3.



[Ref. 19826]

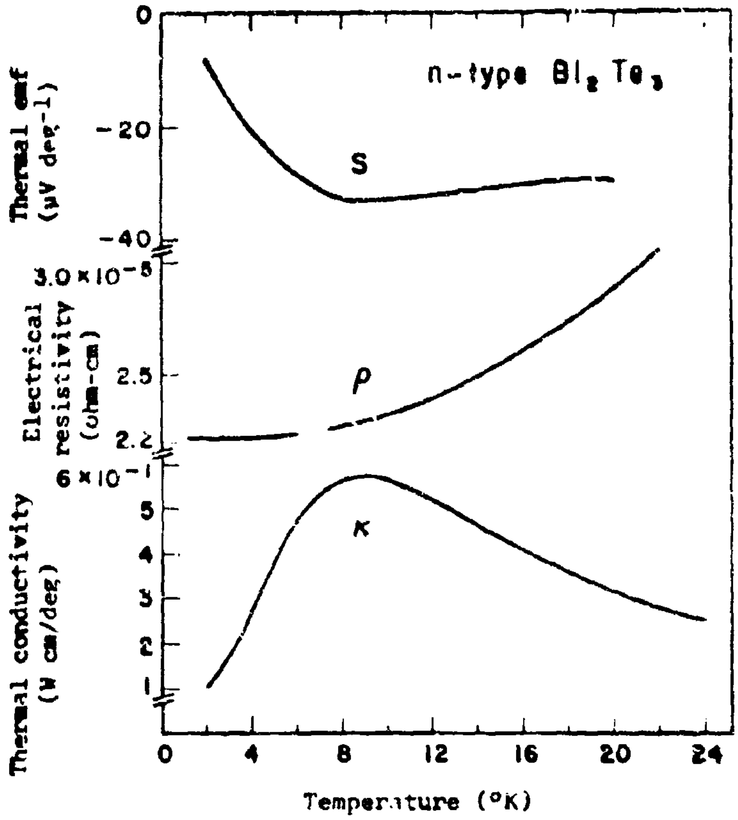


Thermal emf for Bi_2Te_3 single crystal at 300°k as a function of crystal mother liquid composition. Data taken parallel (0001) cleavage plane.

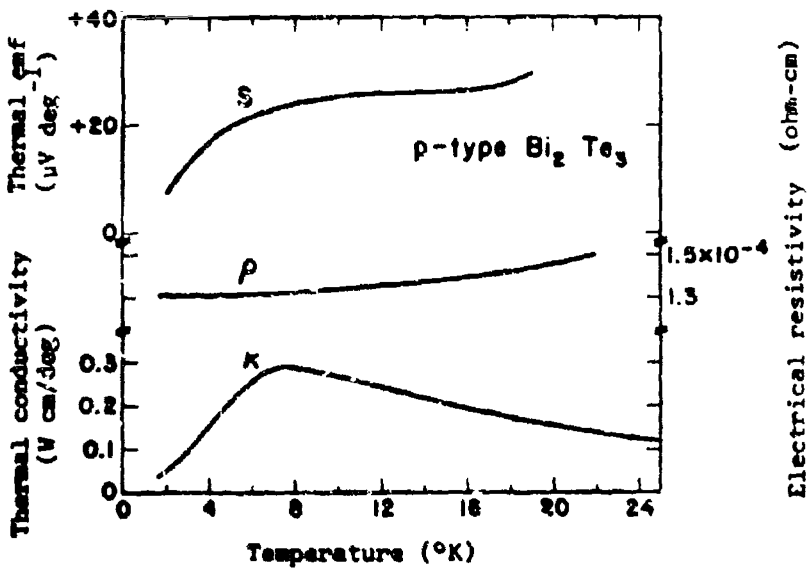
[Ref. 801]

BISMUTH TELLURIDE

THERMOELECTRIC PROPERTIES



Thermal emf, electrical resistivity and thermal conductivity for n- and p-type Bi_2Te_3 as a function of temperature between 2 and 20°K. Carrier concentration for both types was $\sim 10^{19}$/cc.



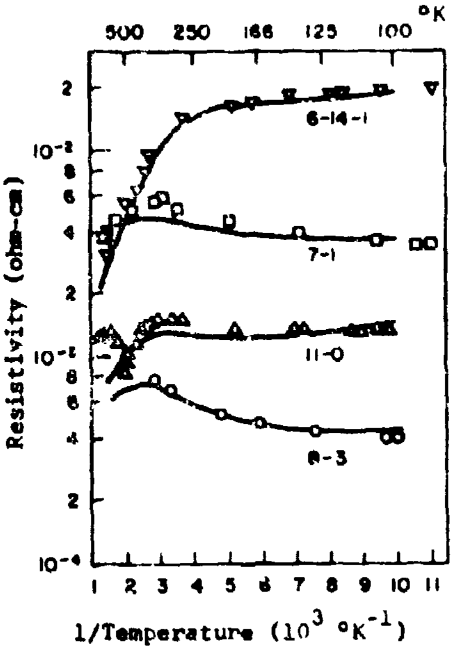
[Ref. 12946]

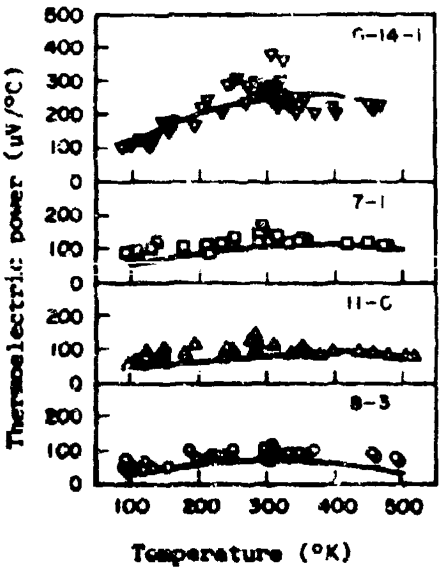
BISMUTH SELENIDE

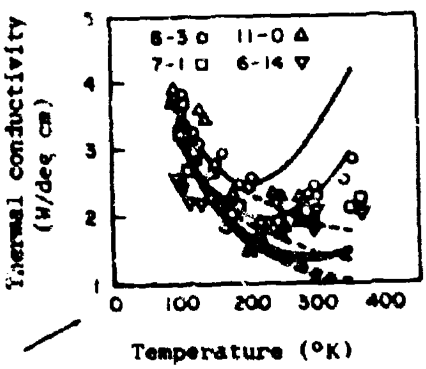
THERMOELECTRIC PROPERTIES

Thermoelectric parameters for polycrystalline, n-type Bi_2Se_3.

Sample	n, cm^{-3}
8-3	5.43×10^{18}
11-0	4.16×10^{18}
7-1	2.97×10^{18}
6-14-1	$.67\times10^{18}$







--- lattice conductivity + normal electronic component

— lattice conductivity + electronic component + normal electronic component

The normal electronic component is a function of conductivity, lattice scattering and sample degeneracy.

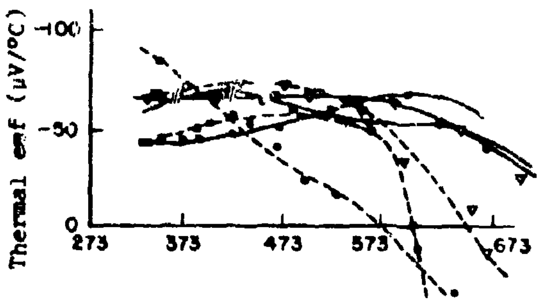
[Ref. 21372]

BISMUTH SELENIDE

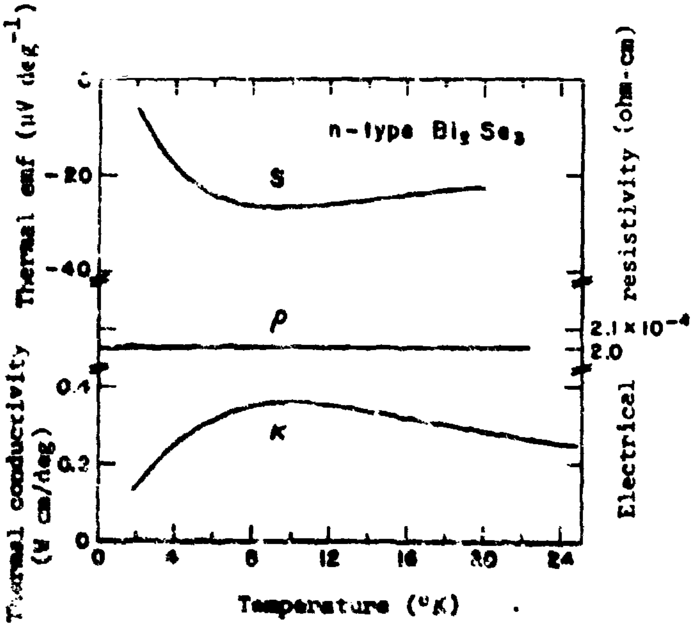
THERMOELECTRIC PROPERTIES

Thermal emf as a function of temperature for single crystal, n-type Bi_2Se_3. Although carrier concentration is the same, the decrease in conductivity of 95-98% from parallel to normal direction, above 500°K, affects the thermal emf. Measurements based on three samples.

Sample cleavage	n, cm^{-3}	σ_{300K}
‖ (0001) ——	$2\text{-}4\times10^{19}$	1000-3000 $(ohm\text{-}cm)^{-1}$
⊥ (0001) ---	"	50-60 "



[Ref. 630]



Thermal emf, electrical resistivity and thermal conductivity in n-type Bi_2Se_3 as a function of temperature from 2 to 24°K. The carrier concentration is $\sim 10^{19}$/cc.

[Ref. 12946]

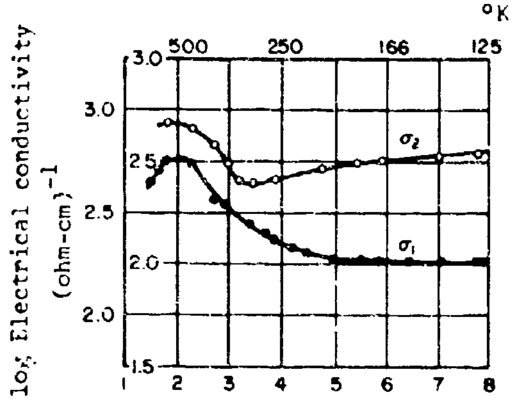
BISMUTH SELENIDE

THERMOELECTRIC PROPERTIES

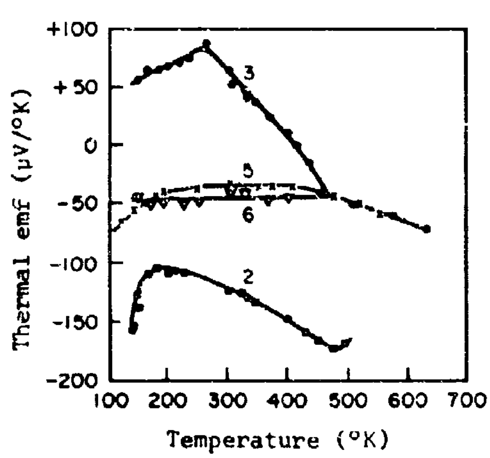
Log electrical conductivity as a function of reciprocal temperature for polycrystalline Bi_2Se_3.

σ_1 is p-type

σ_2 is n-type



[Ref. 2473]



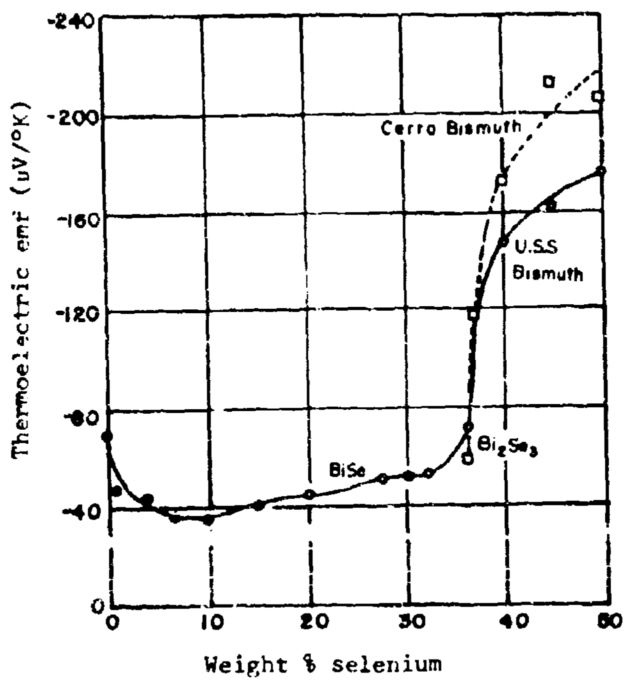
Thermal emf as a function of temperature for polycrystalline Bi_2Se_3, either hot-pressed or from slowly cooled melts.

Sample		n, cm^{-3}
3)	p-type	1.9×10^{19}
2)	n-type	1.6×10^{18}
5)		1.5×10^{19}
6)		1.7×10^{19}

[Ref. 2473]

BISMUTH SELENIDE

THERMOELECTRIC PROPERTIES



Thermoelectric emf (relative to copper) of Bi_2Se_3 alloys as a function of Se content at 300°K. The alloys were macrocrystalline. A high purity grade of selenium was used with two commercial grades of bismuth. The Cerro bismuth purity was higher than that of the USS brand, although the latter was purified before use.

[Ref. 12851]

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RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND

ELECTRONIC PROPERTIES INFORMATION CENTER

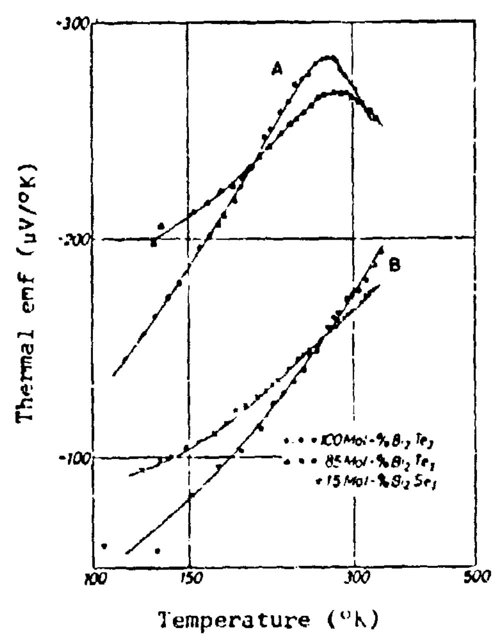
PREPARED BY ELECTRONIC PROPERTIES INFORMATION CENTER • HUGHES AIRCRAFT COMPANY, CULVER CITY, CALIFORNIA

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

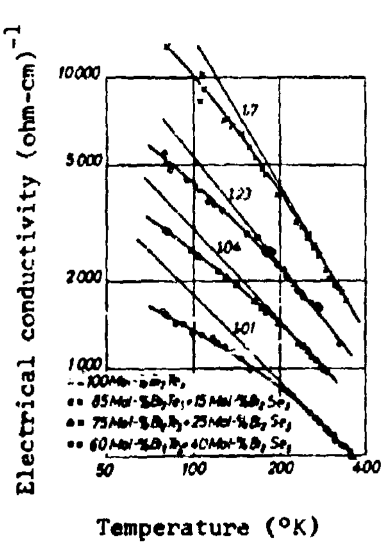
THERMOELECTRIC PROPERTIES

Thermal emf as a function of temperature for single crystal Bi_2Te_3 and single crystal 85% Bi_2Te_3-15% Bi_2Se_3. The normally p-type Bi_2Te_3 is altered to n-type by the presence of the selenide as well as the chlorine.

A) weak doping
B) strong chlorine-doped



[Ref. 5810]



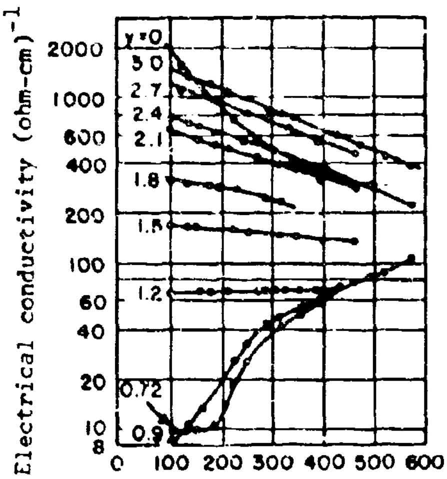
Electrical conductivity as a function of temperature for single crystal samples in the Bi_2Te_3-Bi_2Se_3 system. Chlorine doping is designed to give the maximum figure of merit. The slope of the calculated curves (indicated by integers) gives the temperature coefficient of the electron mobility.

[Ref. 5810]

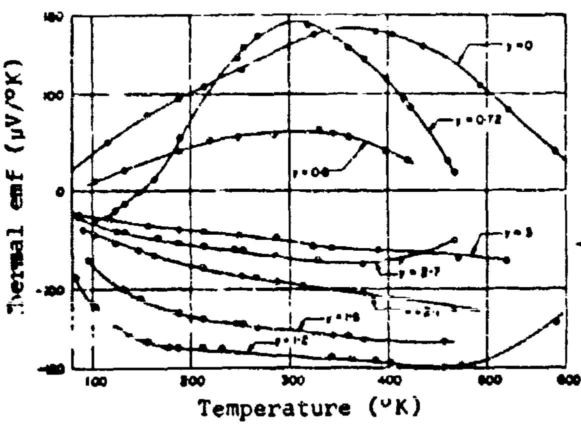
BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

THERMOELECTRIC PROPERTIES

Electrical conductivity as a function of temperature for the $BiTe_{3-y}Se_y$ system.



[Ref. 3449]



Seebeck coefficient as a function of temperature for polycrystalline $BiTe_{3-y}Se_y$ mixed crystals. The crystals are columnar and the measurements are made along the (0001) longitudinal axis.

[Ref. 3449]

The total thermal conductivity of the $BiTe_{3-y}Se_y$ system at 300°K.

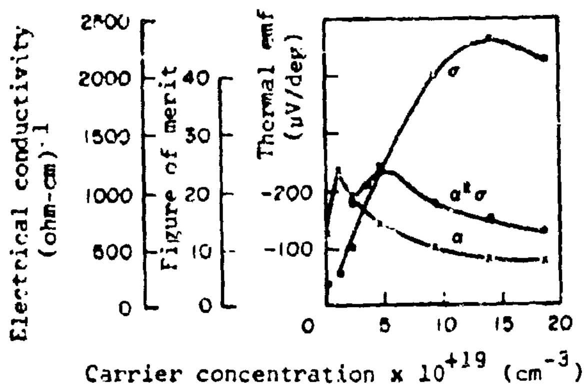
[Ref. 3449]

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

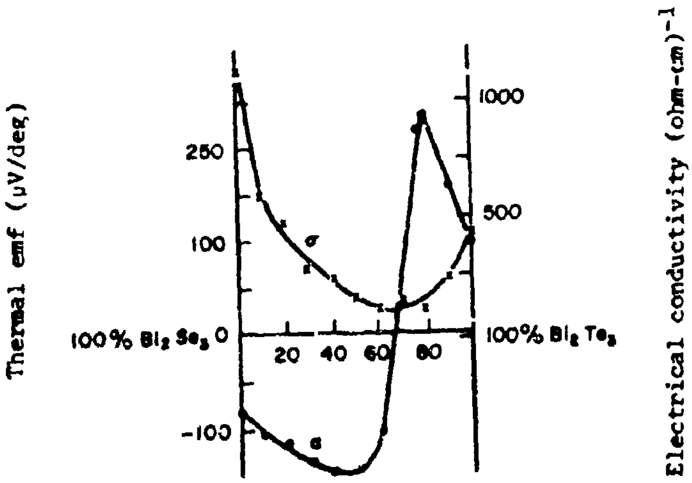
THERMOELECTRIC PROPERTIES

Thermal emf and electrical conductivity as a function of carrier concentration for iodine-doped 80% Bi_2Te_3-20% Bi_2Se_3 at 300°K.

□ σ = Electrical conductivity
o $\alpha^2\sigma$ = Figure of merit
x α = Thermal emf



[Ref. 2538]



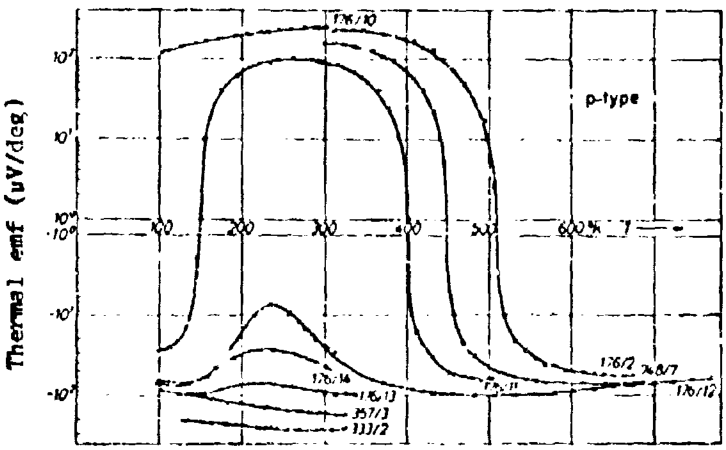
Thermal emf and electrical conductivity as a function of composition in Bi_2Te_3-Bi_2Se_3 macrocrystalline samples.

x = Electrical conductivity
o = Thermal emf

[Ref. 2538]

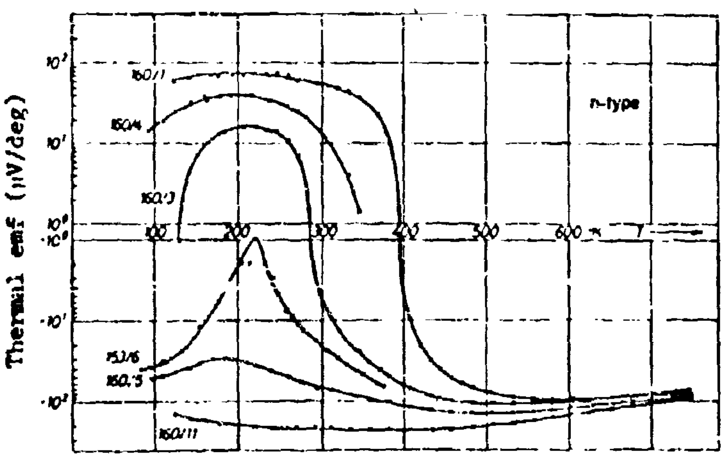
BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Se_{3-x}Se_x$)

THERMOELECTRIC PROPERTIES



Temperature (°K)

$Bi_2Te_{2.7}Se_{0.3}$ (p-type)



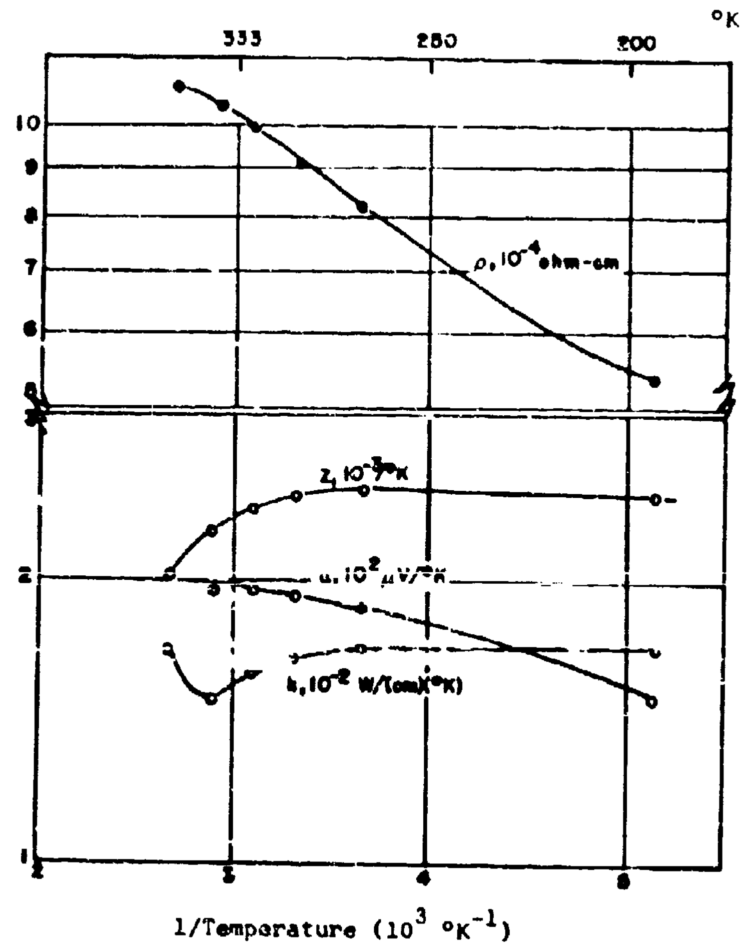
Temperature (°K)

Bi_2Te_2Se (n-type) maximum $n = 3x10^{19}$/cc.

Thermal emf as a function of temperature for compensated single crystal with low carrier concentration. Sample specifications not given. [Ref. 10984]

BISMUTH TELLURIDE-BISMUTH SELENIDE

THERMOELECTRIC PROPERTIES



Thermoelectric properties as a function of reciprocal temperature for 90% Bi_2Te_3-10% Bi_2Se_3, polycrystalline samples.

ρ - resistivity

Q - thermal emf

k - thermal conductivity

Z - figure of merit

[Ref. 15501]

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BISMUTH TELLURIDE-BISMUTH SELENIDE

THERMOELECTRIC PROPERTIES

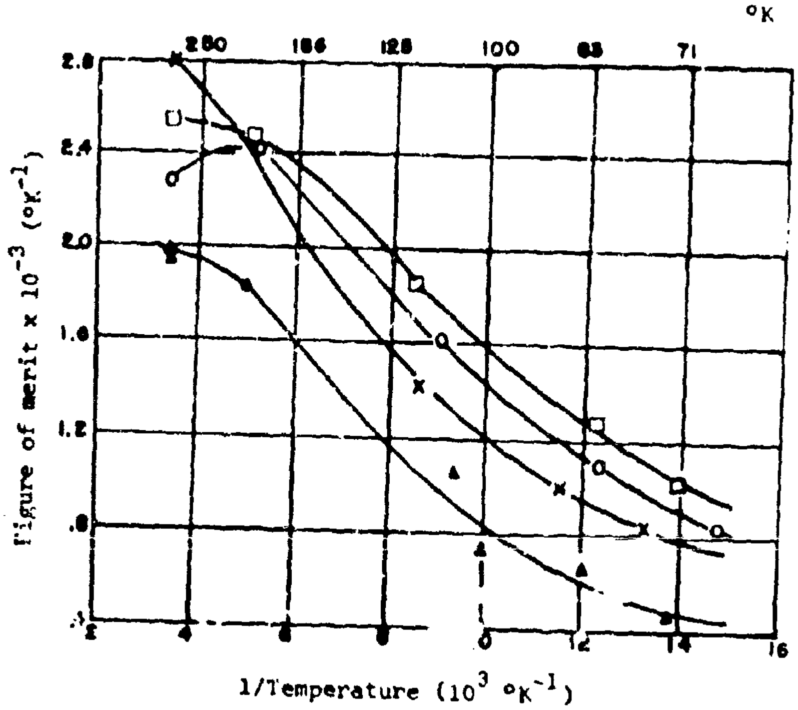


Figure of merit as a function of reciprocal temperature for several Bi_2Te_3-Bi_2Se_3 commercial polycrystalline samples.

□ commercial n-type Bi_2Te_3
Δ p-type, Bi_2Te_3 + 1% Bi
O n-type, Bi_2Te_3 + 5% Bi_2Se_3 + .26% CuBr
X n-type, Bi_2Te_3 + 10% Bi_2Se_3 + .26% CuBr

[Ref. 15503]

BISMUTH TELLURIDE-BISMUTH SELENIDE ($Bi_2Te_{3-x}Se_x$)

THERMOELECTRIC PROPERTIES

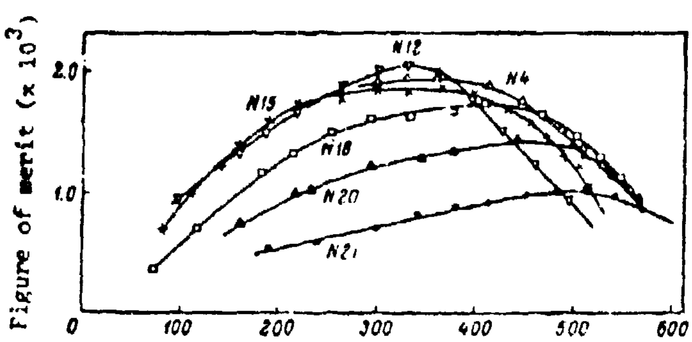


Figure of merit as a function of temperature for polycrystalline samples of Bi_2Te_3(80%)-Bi_2Se_3(20%). n varies from 3×10^{19} to 1.2×10^{20}/cc. Carrier concentrations for samples 15 and 21 are given as:

	n, cm^{-3}
# 15)	4.4×10^{19}
# 21)	3.7×10^{20}

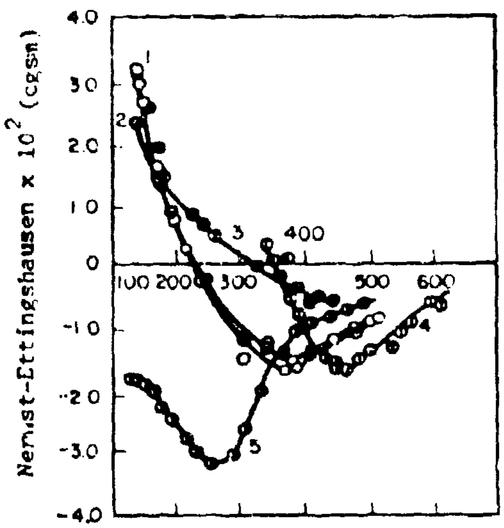
[Ref. 14600]

BISMUTH TELLURIDE and BISMUTH SELENIDE

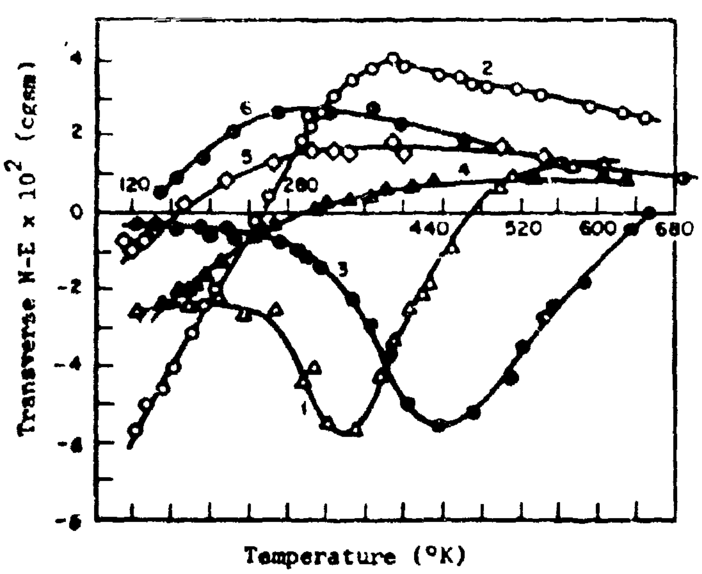
THERMOMAGNETIC PROPERTIES

Nernst-Ettingshausen coefficient as a function of temperature for polycrystalline, cast and pressed Bi_2Te_3, in a 7400 Oe field. Field is applied parallel to (0001) cleavage plane.

Sample	Type	n, cm^{-3}
1	n	1.5×10^{19}
2	n	2.2×10^{19}
3	n	5.5×10^{19}
4	p	6×10^{19}
		4×10^{18}



[Ref. 2537]



Transverse Nernst-Ettingshausen coefficient as a function of temperature for polycrystalline Bi_2Se_3. Material was either hot-pressed or slowly cooled. Carrier concentration at 200°K:

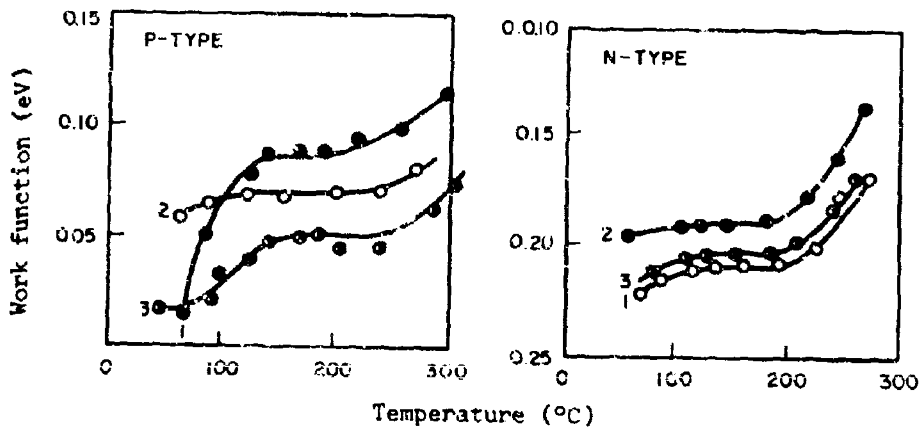
#	Type	n, cm^{-3}
1	p	1.2×10^{19}
3	p	1.9×10^{19}
2	n	1.6×10^{18}
4	n	1.2×10^{18}
5	n	1.5×10^{19}
6	n	1.7×10^{19}

[Ref. 2473]

BISMUTH TELLURIDE

WORK FUNCTION (ϕ)

Value (eV)	Sample	Test Method	Temperature	Ref.
5.30	single crystal, p-type, (0001)	electron photo-emission	300°K	493

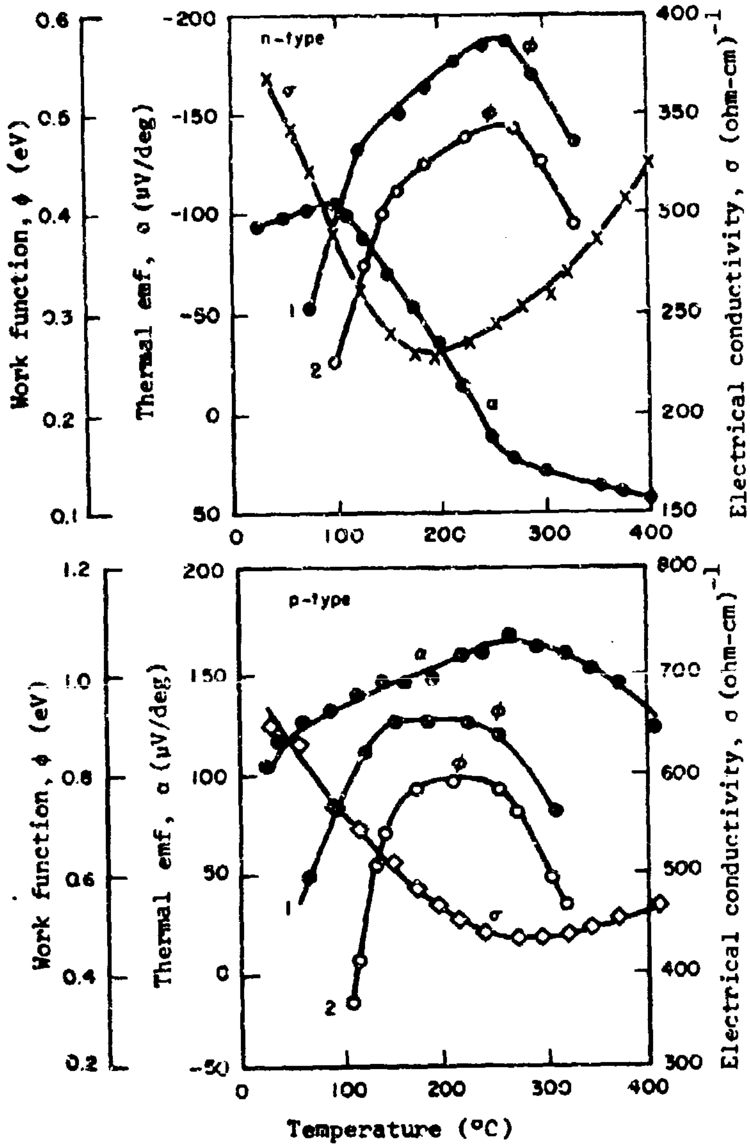


Work function behaviour with temperature for three samples of polycrystalline, n-, and p-type Bi_2Te_3. Measurements made by means of contact potential difference experiments.

[Ref. 19098]

BISMUTH TELLURIDE-BISMUTH SELENIDE

WORK FUNCTION



Work function behaviour with temperature for two samples of polycrystalline, n- and p-type, 80% Bi_2Te_3 + 20% Bi_2Se_3. Conductivity and thermal emf are also shown.

[Ref. 19098]

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ADDITIONAL PUBLICATIONS

EPIC BULLETIN. Vol. 1, no. 1, January 1965- . A monthly two-page news sheet containing items of interest to many of our users.

ELECTRICAL AND ELECTRONIC PROPERTIES OF MATERIALS. INFORMATION RETRIEVAL PROGRAM, Technical Documentary Report No. ASD-TDR-62-539, June 1962, Final Report (Covers work from July 5, 1961 - June 15, 1962), H. T. Johnson, E. Schafer, and E. M. Wallace, pp. 219. (AD-289 546) $15.00.

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(These four reports, ASD-TDR-62-539, Parts I, II, and III, and AFML-TR-65-68, are progress reports that describe the establishment, purpose, operations, programs and accomplishments of EPIC.)

SPECIAL REPORTS

S-1 INSULATION MATERIALS DESCRIPTORS USED IN THE ELECTRICAL AND ELECTRONIC PROPERTIES OF MATERIALS INFORMATION RETRIEVAL PROGRAM: Emil Schafer. July 1962. (Superseded by other publications.)

S-2 SEMICONDUCTOR MATERIALS DESCRIPTORS USED IN THE ELECTRICAL AND ELECTRONIC PROPERTIES OF MATERIALS INFORMATION RETRIEVAL PROGRAM: Emil Schafer. September 1962. (Superseded by other publications.)

S-3 A SURVEY MATERIALS REPORT ON TETRAFLUOROETHYLENE (TFE) PLASTICS. J. T. Milek. September 1964. (AD-607 798) $4.00.

S-4 THE PURPOSE AND FUNCTIONS OF THE ELECTRONIC PROPERTIES INFORMATION CENTER. H. Thayne Johnson. August 1964. (out of print)

S-5 ELECTRON MOBILITY IN ALIPHATIC HYDROCARBONS AS RELATED TO ORGANIC INSULATION BREAKDOWN. J. T. Milek. February 1965. (AD-465 159) Not available from Clearinghouse.

S-6 OPTICAL PROPERTIES AND THERMAL CONDUCTIVITY OF ALUMINUM OXIDE. M. Neuberger. February 1965. (AD-464 825). Not available from Clearinghouse.

S-7 GLOSSARY OF ELECTRONIC PROPERTIES. Emil Schafer. January 1965. (AD-616 785) $3.00.